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ORIGINAL PAPER

Field investigation of the feasibility of MICP for Mitigating Natural Rainfall-Induced erosion in gravelly clay slope

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Abstract

Rainfall-induced erosion on slopes is a prevalent natural process leading to soil loss. One promising application of microbially induced carbonate precipitation (MICP) is to mitigate rainfall-induced erosion. Conducting field tests is an essential step to verify and improve its performance. In the current work, field tests were conducted to assess the feasibility of using MICP to mitigate rainfall-induced erosion on a gravelly clay slope in Longyan, Fujian, China. A temporary laboratory was set up to cultivate bacteria, and a non-sterilizing method was employed to prepare large volumes of bacterial suspensions in a single batch. Slopes were treated by spraying solutions onto their surfaces. The amount of discharged soils and 3D surface scanning results were used for evaluating the erosion intensity of the slopes. The results demonstrated that the method could effectively mitigate the surface erosion caused by natural rainfall and prevent erosion-induced collapse. Notably, approximately one year after the treatment, the grass had started to grow on the heavily cemented slope, indicating that the MICP method is both effective and eco-friendly for soil stabilization method. However, further improvements are needed to enhance the uniformity and long-term durability of the MICP treatment.

Keywords Slope protection · MICP · Field tests · Natural rainfall-induced erosion · 3D scanning

Introduction

Soil loss is a critical environmental issue that can negatively impact water quality, food production, ecosystem, and property security. In China, approximately 37% of the land area (3.6×10^6 km^2) is affected by soil loss (Panagos et al. 2015; Yang et al. 2018). Several factors can lead to soil erosion, including wind, rainfall, tides, river flow, and underground flow (Benavidez et al. 2018; Fleshman and Rice 2014; Muchena et al. 2005; Prăvălie 2021; Shen et al. 2016; Wu et al. 2017). Among them, rainfall-induced erosion plays a significant role in inland soil loss (Duan et al. 2020; Liu et al. 2019), leading to numerous environmental and geotechnical challenges, such as land deterioration, water contamination, landslide, and collapsing (Cemiloglu et al. 2023; Mao et al. 2023; Nanehkaran et al. 2021, 2023a, b). Consequently, controlling soil erosion is a challenge faced by countries worldwide. Various methods have been developed to mitigate soil erosion, including biological approaches (such as vegetation and biofilm), as well as physical and chemical methods (Jiang and Soga 2017; Liu et al. 2022; Liu and Hou 2023; Wei et al. 2022; Yan et al. 2021). However, various challenges arise during the application of these techniques (Jiang et al. 2019; Sun et al. 2021c; Wang et al. 2020, 2023), highlighting the need for the development of an effective and eco-friendly approach to improve soil erosion control.

Microbially induced carbonate precipitation (MICP) is a promising method recently proposed for soil stabilization (Chu et al. 2012; DeJong et al. 2006; Gao et al. 2018; Liu et al. 2024; van Paassen et al. 2010; Zhang et

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al. 2024; Zhao et al. 2023). The method utilizes harmless microbes to induce the precipitation of inorganic minerals, such as calcium carbonate ($CaCO_3$) (He et al. 2020; Lv et al. 2022; Qabany and Soga 2013). One of the most commonly used methods involves the hydrolysis of urea, i.e., $CO(NH_2)_2 + H_2O \xrightarrow{\text{bacteria}} 2\,NH_4^{+} + CO_3^{2-}$, by which $CaCO_3$ precipitates with the presence of Ca^{2+}, i.e., $Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3$ (Gomez et al. 2017; Peng and Liu 2019). The precipitated $CaCO_3$ in soil pores can bond soil particles together, forming rock-like structures that can help soils resist external loadings, such as those from buildings, machinery, rainfall, runoff, and wind (Ma et al. 2022). As a result, the MCIP method has broad application prospects, including foundation stabilization, seepage control, crack repair, and erosion control (Cheng and Shahin 2017; Cui et al. 2020; Fattahi et al. 2020; Han et al. 2022; Sun et al. 2021b; Wu et al. 2019; Xiao et al. 2021; Yang et al. 2022). Among these, erosion control is one of the most important applications of MICP, as even a small amount of precipitate can substantially improve soil resistance to erosion caused by rain, wind, seepage, and waves (Almajed et al. 2020; Fattahi et al. 2020; Haouzi et al. 2019; Jiang and Soga 2017; Li et al. 2019; Shahin et al. 2020; Sun et al. 2021a; Wang et al. 2018; Xiao et al. 2022b).

Although numerous studies have investigated the feasibility of MICP for protecting slope surfaces composed of various soil types and gradations through model tests, little research has been conducted on actual field slopes. However, field tests are a necessary step to verify and enhance the performance of MICP in protecting slope surfaces from erosion. On the one hand, real slopes are significantly larger than slope models; on the other hand, the slope surfaces are typically treated by spraying methods, often manually. Furthermore, previous studies have mainly characterized slope erosion under artificial rainfall conditions, in which the rainfall was typically intensified and the tests were completed over short periods, neglecting the long-time durability of the MICP treatment (Jiang et al. 2019; Liu et al. 2021b; Xiao et al. 2022a). However, under natural conditions, the MICP-treated slopes are subjected to physical (e.g., temperature fluctuations, variations in saturation degree, and salt transport and crystallization), chemical (e.g., acid rain), and biological (e.g., plant growth) weathering (Ji et al. 2024). Consequently, these model tests may not accurately represent the real erosion characteristics of slopes treated with MICP.

The aim of the current work was to evaluate the feasibility of using MICP to mitigate rainfall-induced erosion on slopes composed of gravelly clay under natural conditions through field tests. The work allows for a comprehensive assessment of the influences of real rainfall conditions, weather changes, and the durability of the MICP treatment. The test was conducted at a construction site located in Longyan, Fujian, China, as shown in Fig. 1a, as part of a slope protection project by the Fujian Geological Engineering Survey Institute. The area is characterized by hilly

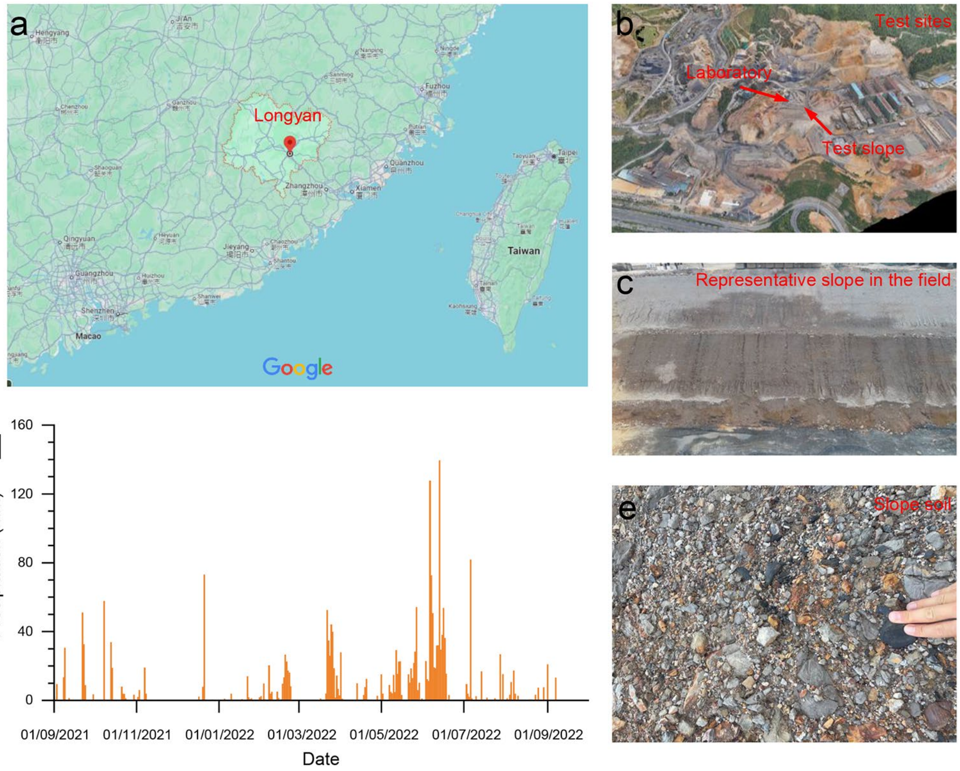


Fig. 1 Field test site and the rainfall intensity during the field tests

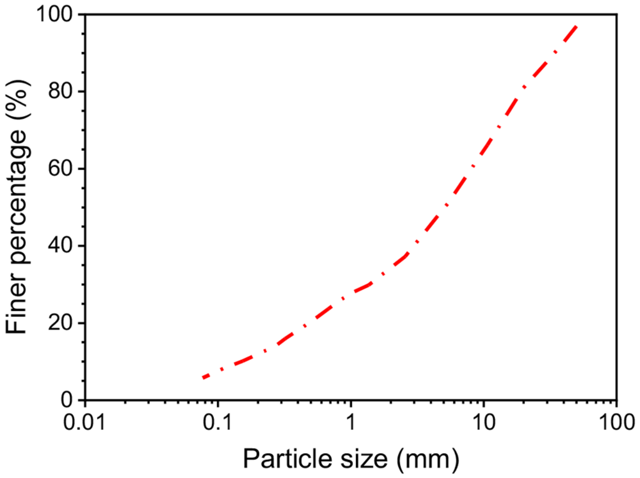


Fig. 2 Particle size distribution curve

terrain with elevations ranging from 431.42 m to 489.67 m, resulting in an altitude difference of 58.25 m. The region experiences a subtropical oceanic monsoon climate, with an average annual temperature of 20.5 °C and annual precipitation of approximately 1479 mm. The soils at the site primarily consist of silty clay, gravelly silty clay, and artificial backfill. Due to the large size of the construction site, numerous excavated slopes are present (Fig. 1b). Many of these slopes will remain exposed for an extended period due to the lengthy construction timeline. During this time, the rainfall-induced erosion of the slopes in the construction sites cannot be overlooked. As shown in Fig. 1c, numerous gullies have already formed on the slopes, indicating significant erosion, which not only contaminates the site, adversely affecting the overall working environment, but also poses a risk to slope stability. Therefore, it is essential to develop a convenient, eco-friendly, and cost-effective method to mitigate rainfall-induced erosion on these temporary slopes.

Details for the field tests

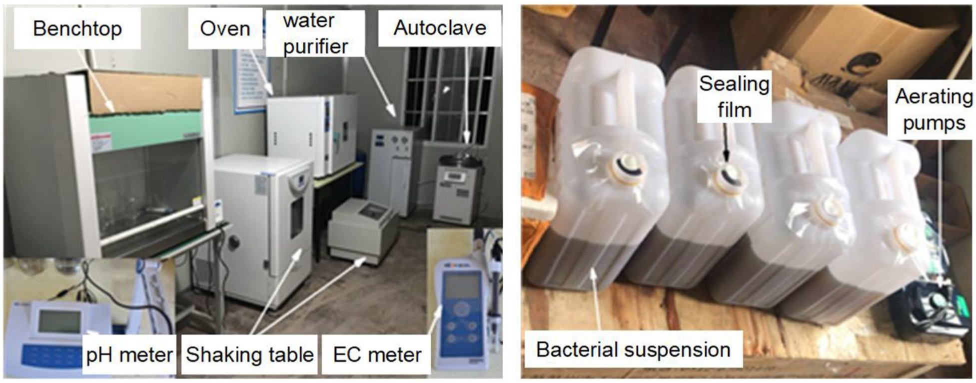
Characteristics of the test slope

The slope of the tested area was approximately 45°. The surface soils were backfilled after the excavation of the construction site. The backfilled soil was mainly composed of gravel and clay Fig. 1e. The gravel sizes ranged mostly between 10 mm and 50 mm, accounting for approximately 50% by weight of the backfilled soil. The particle size distribution curve of the slope soil is shown in Fig. 2. The average compaction degree of the backfilled soils was 92%. The cohesive strength and inner friction angle were 31 kPa and 39.7°, respectively. The permeability of the soil was measured at 5×10^{-5} cm/s. Beneath the surface soils, the underlying rock consisted mainly of strongly to moderately weathered mudstone and siltstone. There was no underground water present on the slope. The field tests were carried out from 01/09/2021 to 31/01/2022, with additional visual observations extending to 01/09/2022. Precipitation during the research period is shown in Fig. 1d.

Preparation of bacterial suspensions and cementation solutions

The cultivation of bacteria was conducted in a temporary laboratory established in a prefabricated house near the slope, as marked in Fig. 1b. The equipment used included the benchtop, autoclave, shaking tables, refrigerator, water purifier, oven, pH meter, electrical conductivity meter (EC meter), buckets, and aerating pumps, as shown in Fig. 3. The temperature in the laboratory was controlled to 25 °C using an air conditioner. The bacteria used was *Sporosarcina pasteurii* (CGMCC 1.683). The culture medium consisted of 20 g/L yeast extract/soybean peptone, 10 g/L NH_4Cl, 12 mg/L $MnSO_4\cdot H_2O$, 24 mg/L $NiCl_2\cdot 6H_2O$, and 1.5 g/L agar (for solid culture medium only). The pH of the culture medium was adjusted to 9.0 using 1 mol/L NaOH solutions.

Fig. 3 Test equipment in the temporary laboratory and the prepared bacterial suspension



The specific steps for the cultivation of bacteria were as follows:

1) Activation of the bacterial strain: Autoclave the yeast extract culture medium at 121 °C for 30 min, and then cool the culture medium to room temperature under ultraviolet light on the benchtop. The purchased solid bacterial strain was inoculated into the sterile culture medium and incubated at 30 °C with shaking at 200 rpm for 24 h.
2) Culturing and storage: After harvesting, a portion of the bacteria was inoculated onto a solid culture medium, which was further incubated at 30 °C for approximately two days. Another portion of the bacteria was stored in glycerin at -20 °C, which was used for preparing solid culture mediums for future cultivation.
3) Cultivation of precursor bacterial suspension. 100 mL of yeast extract culture medium was prepared in an Erlenmeyer flask. The bacteria from the solid culture medium were used for inoculation, following the same procedure as for the initial activation.
4) Non-sterilizing cultivation of large-volume bacterial suspension. Due to the challenges of sterilizing large volumes of culture medium in the field, sterile cultivation was not feasible. Instead, a non-sterilizing method was employed during the field tests. However, to minimize contamination, ultraviolet light was used to sterilize the laboratory environment for 30 min before preparing the culture medium. Approximately 10 L of soybean peptone culture medium was then prepared in a 20 L bucket (Fig. 3), and the previously harvested 100 mL bacterial suspension was directly added. Porous stones connected to an aerating pump via soft tubes were placed in the bucket, and the mouth of the bucket was sealed with a sealing film. Air was continuously pumped into the culture medium during cultivation. The bacteria were cultivated at room temperature, controlled by an air conditioner, for approximately 24 h. After harvesting, the bacteria were stored at 4 °C before use.

The urease activity of the bacteria was tested using the electric conductivity method before each treatment, which was approximately 1.5 mmol urea/min (Ma et al. 2021a). The cementation solutions contained 1 mol/L $CaCl_2$ and 1 mol/L urea (Yu and Rong 2022; Yu et al. 2022).

Test design and characterization

To investigate the effect of MICP cementation levels on the anti-erosion behavior of the slope, the slope was divided into three test areas, as shown in Fig. 4a. Each test area measured 5.6 m in length, 2 m in width, 4 m in height, with a slope angle of 45°. The areas were enclosed with PVC sheets, and an eave was installed at the bottom of each test area to collect surface runoff and eroded soil into a 100 L bucket, as shown in Fig. 4b. From left to right, the areas were designed as untreated, highly cemented, and weakly cemented. The highly cemented area received 12 treatment cycles, while the weakly cemented area received 6 treatment cycles.

The stabilization of the slope surface was achieved using a spraying method, where specially designed equipment was employed to spray both bacterial and cementation solutions, as detailed in Xiao et al. (2022b). During each treatment cycle, approximately 0.75 L/m^2 of bacterial solution and 2.25 L/m^2 cementation solution were sprayed on the slope surface aiming for a target stabilization depth of

Fig. 4 Photographs showing (**a**) the envelopment of slopes, (**b**) the collection of surface runoff and eroded soils, (**c**) the covering of the slope surface during MICP treatment, and (**d**) 3D scanning of the slope surface

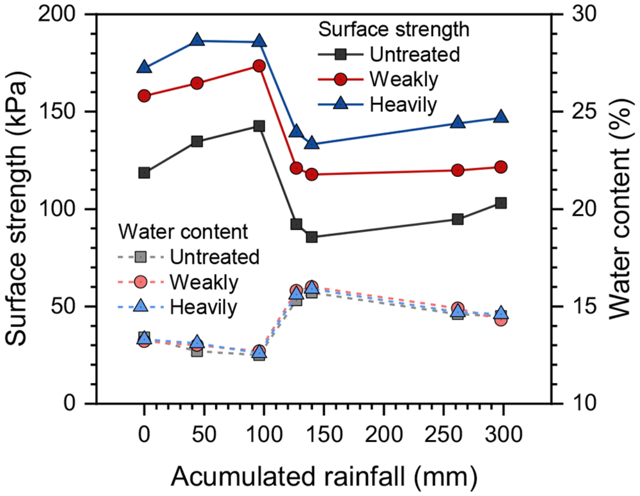


Fig. 5 Variations of surface strength with accumulated rainfall

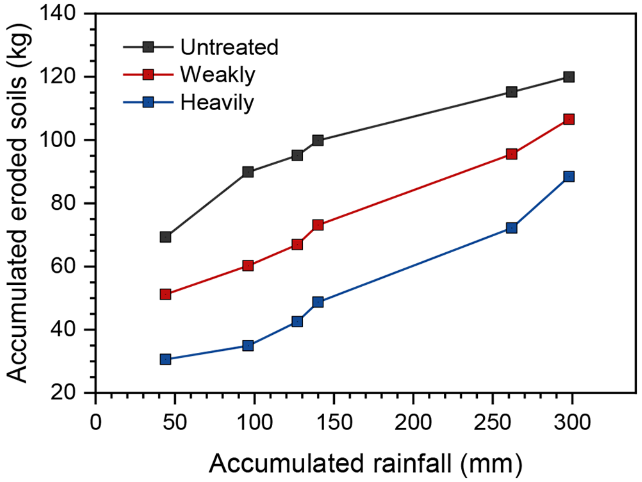


Fig. 6 Variations of the mass of eroded soil with the accumulated rainfall

about 1 cm. The interval between successive treatments was about 6 h to ensure full reaction of the cementation solutions during daylight hours. Due to the difficulty of conducting treatments at night, the intervals between treatments were relatively long. After the MICP treatment, the slopes were covered with a layer of film to prevent evaporation during curing and to protect against rainfall-induced erosion before data collection, as shown in Fig. 4c.

To characterize the performance of MICP in mitigating slope erosion, the surface strength, the weight of eroded soils, and the geometries of the slope surface were measured. The surface strength was assessed using a miniature penetrometer after treatment and following heavy rainfall on the dates of 16/09/2021, 23/09/2021, 24/09/2021, 01/10/2021, 22/10/2021, and 05/11/2021. Since surface strength can vary with soil moisture content, sensors were installed in the slope before MICP treatment to monitor soil water content.

After heavy rainfall on the aforementioned dates, the weight of the eroded soils was determined by collecting surface runoff into 100 L buckets, directed by several PVC plates as shown in Fig. 4b. As there was sufficient time, the collected runoff was allowed to settle so that the eroded soils could precipitate. The clear top water was then removed, and the remaining sediments were oven-dried and weighed. However, the mass of the eroded soils provides only a general indication of overall erosion. To obtain more detailed information on erosion intensity across the slope surface, the slopes were scanned using a 3D laser scanner (FARO Focus S), which is a high-speed, pulse-type, high-precision device. The laser scanner has an accuracy of less than 4 mm for distance measurement and less than 12″ for angle measurement. The scanned data were then transformed into a BIM model, allowing for a quantitative analysis of slope erosion. The error margin for the established surface BIM models was less than 2 mm. The laser scanning was performed on 04/09/2021 (after treatment), 23/09/2021, 22/10/2021, 05/11/2021, and 07/01/2022.

Test results and discussion

Variations of surface strength and water content

Surface strength is a common indicator used to assess the effectiveness of MICP in mitigating slope erosion (Chung et al. 2021; Lu et al. 2021; Sun et al. 2021c; Xiao et al. 2022b). The variations in surface strength with accumulated rainfall are presented in Fig. 5. Although surface strength varied with accumulated rainfall, the surface strength of the highly cemented slope consistently remained higher than that of the weakly cemented slope, which in turn was higher than that of the untreated slope. These variations in surface strength were closely linked to climate conditions. For instance, surface strength decreased following rainfall but increased after prolonged exposure to sunlight. The corresponding water content results are also displayed in Fig. 5, clearly showing that surface strength was inversely related to the water content of slope soils, which was also previously demonstrated through UCS tests by Ma et al. (2021b).

Evolution of eroded soils

Although surface runoff was collected during rainfall, the volume of water varied significantly due to factors, such as water infiltration into the soil and direct collection of rainfall. As a result, the collected water did not accurately reflect the erosion characteristics of the soil slopes. Therefore, only the mass of the eroded soils is presented in Fig. 6. As expected, the eroded soils from the MICP stabilized slopes were less than those from the untreated slope, with erosion decreasing as cementation levels increased. Specifically, the mass of the accumulated eroded soil from the weakly cemented slope ranged from approximately 60–88% of that from the untreated slope, while the mass from the heavily cemented slope ranged from approximately 38–73% of the untreated slope. It is evident that soil erosion was still relatively significant even for the heavily treated slope. This could be attributed to the non-uniform distribution of precipitates, which led to uneven erosion on the slope surfaces, as illustrated by 3D scanning results presented later. In addition, it is noteworthy that erosion on the MICP-treated slopes was initially less severe compared to the untreated slopes. However, after 250 mm of rainfall, the erosion on the treated slopes appeared to be more pronounced than on the untreated slopes, as evidenced by the steeper slope of the erosion curves. The results indicated that the performance of the method at a long duration was not as effective as that observed in model tests when used to protect slopes composed of fine soils in a short period (Cheng et al. 2021; Liu et al. 2021b; Lu et al. 2021; Sun et al. 2022). The reason can be attributed to variations in water content and temperature, which can lead to cracking in the crust formed on the slope surfaces (Ji et al. 2024).

Details of the surface erosion

Photos of the slope after MICP treatment and after four months of erosion are shown in Fig. 7b and c, respectively. The natural rainfall-induced erosion tests began on 04/09/2021, and continued until the end of January 2022. As seen in the photos, erosion was relatively severe in all three test areas. The gullies formed prior to erosion had disappeared, leaving the slopes more flattened. In addition, the sediment collected in the bucket beneath the untreated slope was the greatest, while that beneath the heavily stabilized slope was the least. Beyond these observations, the photos provide limited information.

To obtain more detailed insights into the erosion of the slopes, the slope surfaces were scanned using a 3D scanner. The first 3D scan was conducted on 04/09/2021 and served as the reference. The second scan was performed on 23/09/2021, following three heavy rains on 08/09/2021, 09/09/2021, and 22/09/2021 before scanning. The third scan was conducted on 22/10/2021, after four intense rains on 08/10/2021, 12/10/2021, 14/10/2021, and 21/10/2021. The fourth scan was conducted on 05/11/2021, following five heavy rains on 23/10/2021, 30/10/2021, 02/11/2021, 03/11/2021, and 07/11/2021. The fifth scan was performed on 07/01/2022, after two strong rains on 20/12/2021 and 21/12/2021.

The erosion intensity was quantitatively analyzed by subtracting the data collected from the original slope, as shown in Fig. 8a – 8d. In the figures, red areas indicate sediment accumulation, while blue areas represent slope surface erosion. It is clear that both the extent and intensity of the blue areas increased with increasing precipitation, indicating that erosion intensified with more rainfall in all three test areas. Furthermore, the untreated slope exhibited the most severe erosion, followed by the weakly treated slope, with the least erosion observed on the heavily treated slope. These results are consistent with the data on accumulated eroded soils. It appears that the performance of biocementation in mitigating rainfall-induced erosion of fine-grained soil was not particularly effective. This finding aligns with previous research. For example, Sun et al. (2021c) applied enzyme-induced carbonate precipitation (EICP) on slopes with soil particle sizes ranging between 5 and 50 μm. The accumulated mass of eroded soils exceeded 750 g after 40 min of rainfall, and the model slope began to collapse during the rain.

Long-term visual observation

Although no further quantitative analysis was conducted after 07/01/2022, the slope was left undisturbed, and additional photos were taken on 01/03/2022, 08/04/2022, and 28/09/2022. To further analyze the influence of rainfall on the long-term anti-erosion properties, precipitation data during this period were also collected, as shown in Fig. 7a. First of all, the morphology of the slope did not change significantly during the quantitative analysis period from 01/09/2021 to 07/01/2022, as shown in Fig. 7b and c. However, after a small amount of rain from 07/01/2022 to 01/03/2022, the untreated slope began to fail, as shown in Fig. 7d. The slope collapsed from the toe after approximately six months from the start of the test due to rainfall-induced erosion. From 01/03/2022 to 08/04/2022, the slopes did not undergo substantial changes, as seen in Fig. 7e. However, during the period from 08/04/2022 to 28/09/2022, the weakly cemented slope also failed from the toe, as shown in Fig. 7f. Notably, the precipitation during this period was particularly heavy, with approximately 447.9 mm of rainfall recorded from 24/05/2022 to 15/06/2022, breaking the record since 1961 (https://fjrb.fjdaily.com). Fortunately, the heavily cemented slope remained intact even after a total of approximately 2500 mm of rainfall, with the slope surface geometry showing no significant changes compared to the photo taken on 07/01/2022. This phenomenon indicates that MICP is indeed an effective method for mitigating rainfall-induced erosion and preventing the collapse of gravelly clayey slopes.

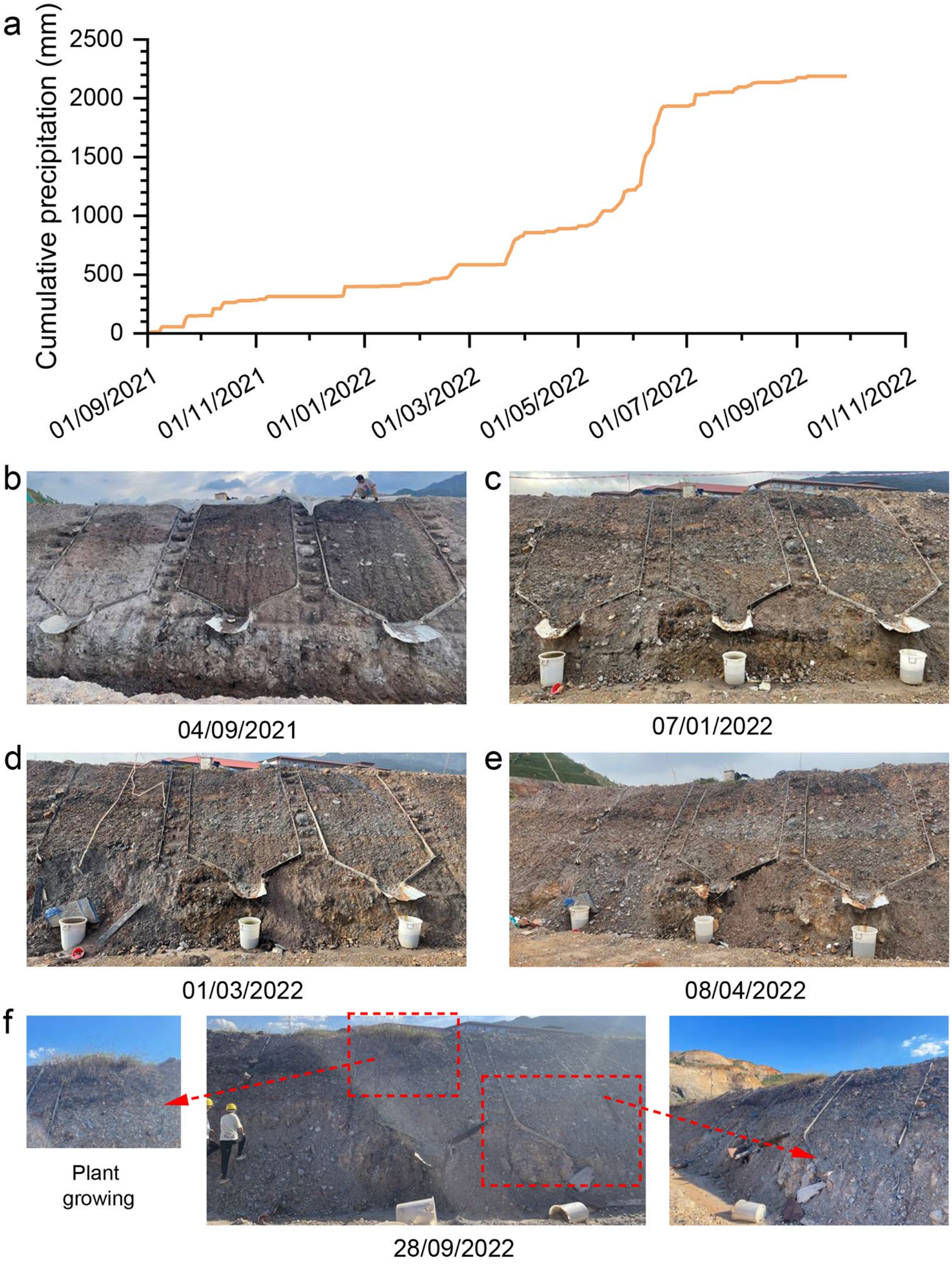


Fig. 7 (**a**) The variations of the cumulative precipitation with time, and photos taken at (**b**) 04/09/2021, (**c**) 07/01/2022, (**d**) 01/03/2022, (**e**) 08/04/2022, and (**f**) 28/09/2022

Similar observations have been made in model tests by Wang et al. (2020) and Phanvongsa et al. (2023), who reported the effectiveness of MICP in delaying the failure of sand embankment slopes and preventing the collapse of cut sandy slopes caused by rainfall-induced erosion, respectively. However, in the current work, this is the first time that the efficacy of MICP for delaying the failure of in-situ clayey slopes due to natural rainfall has been observed. The ability of MICP to delay slope failure can be attributed to two factors. First, a crust layer was formed on the slope surface after MICP treatment, including a $CaCO_3$ crust and cemented surficial soils (Buikema et al. 2018; Liu et al. 2021b; Saracho et al. 2021; Wang et al. 2020; Xiao et al. 2022b). This crust enhances the resistance of the slope to external loading, with its effectiveness depending on the thickness and uniformity of the crust. Second, the protective crust reduces water infiltration, as observed by Xiao et al. (2022a), which significantly delays slope collapse (Liu et al. 2023; Wang et al. 2022). However, the long-term stability of the MICP treated surface was not that good. As reported by Ji et al. (2024), the surface will suffer wet-dry and temperature change cycles, the integrity of MICP treated slope surface would be gradually degraded with time. In addition, the infiltrated water would also increase with the deterioration

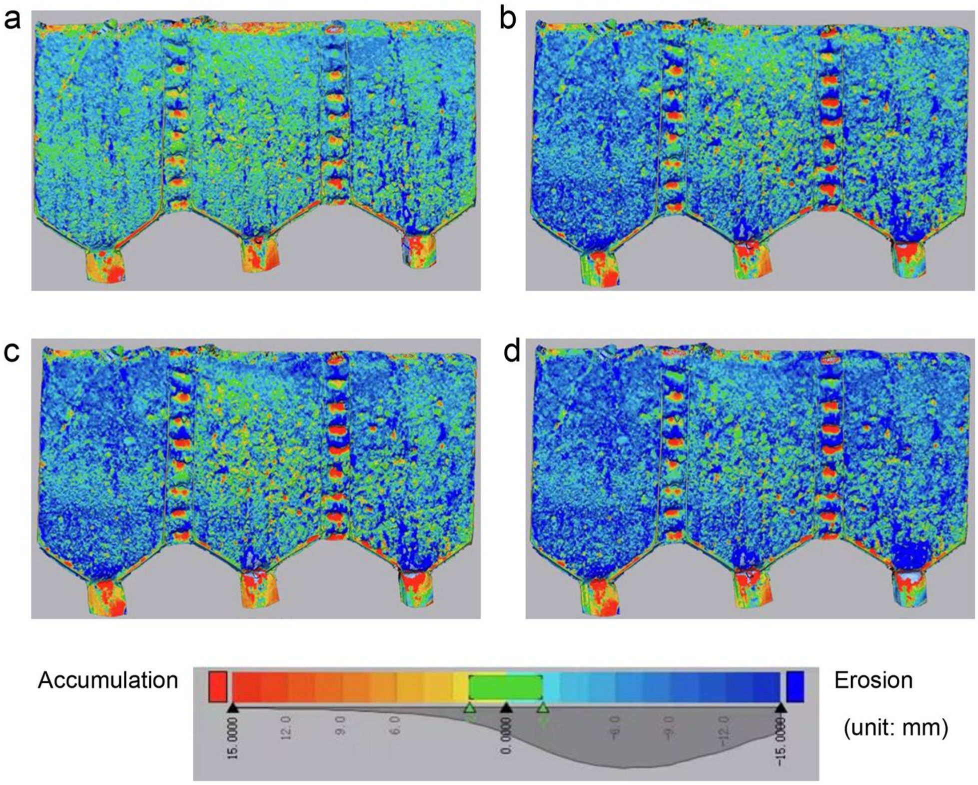


Fig. 8 (**a**) - (**d**) The erosion depth on the slope surfaces after strong rain taken on 09/23/2021, 22/10/2021, 05/11/2021, and 07/01/2022, respectively

of surficial crust. As a result, the erosion of soil surface increased and the slope collapsed after a certain period, as shown in Figs. 6 and 7.

In addition to long-term performance in resisting rainfall-induced erosion, ecological compatibility is another critical consideration when applying MICP for slope surface protection (Xiao et al. 2023). However, limited field tests have been conducted to assess ecological compatibility. For example, Zhan et al. (2016) examined the growth (bud rate and appearance) of soybeans in MICP-treated soils and compared it with that in water-treated soils. Sun et al. (2021a) observed the growth of seeds on MICP-treated soils and untreated soils in the Tengri Desert area. Both studies reported better seed growth after artificial seeding on MICP-treated soils compared to untreated soils. This could be attributed to the residual urea, which serves as a fertilizer, and the enhanced water retention properties of MICP-treated soils (Chen et al. 2021; Liu et al. 2021a; Saffari et al. 2019). However, artificially seeding after MICP treatment is not always feasible, as it can compromise the integrity of the surface crust, leading to a reduction in erosion resistance. Therefore, the natural growth of wild plants becomes a crucial factor in evaluating the ecological compatibility of MICP. Meng et al. (2021) observed the growth of wild sand vegetation on the treated sites without any artificial seeding and irrigation. In this work, it is noteworthy that grass naturally grew on the heavily cemented slope as well. This is an encouraging result, as it suggests that MICP does not cause long-term environmental damage. The ecosystem can recover naturally after slope stabilization, demonstrating that the MICP method is both effective and eco-friendly for soil stabilization.

Although vegetation growth may disrupt the protection crust created by MICP, the grass itself can offer additional protection. As reviewed by Wang et al. (2021), vegetation can shield soil from raindrops and block runoff, thereby protecting soil particles from raindrop-induced splashes and runoff-induced transport. In addition, plant roots can consolidate the soil and reduce water infiltration, thereby improving slope stability and preventing soil erosion (Römkens et al. 2002). The results of the current work also suggest that combining temporary MICP treatment with long-term plant protection can be a more effective strategy for slope protection.

Implications

Effectiveness of biotreatment on slopes with varying soil types

The effectiveness of MICP in mitigating rainfall-induced erosion on slopes composed of different soil types and gradations has been demonstrated through model tests. First of all, MICP has proven to be particularly suitable for stabilizing sandy soils, making it highly effective in mitigating erosion on sandy slopes (Liu et al. 2022; Shih et al. 2019; Wang et al. 2020). However, the performance of MICP in erosion control is significantly affected by the gradation and composition of the sandy soils. For example, Xiao et al. (2022a) found that MICP was effective in mitigating erosion on well-graded sand slopes, while negative results were observed on poorly graded coarse sand slopes due to enhanced surface runoff. Chung et al. (2021) showed that MICP could be applied to mitigate rainfall-induced erosion on sandy and sandy loam slopes, while the presence of organic matter, even in limited amounts, weakened its performance. While MICP is generally less effective for stabilizing clay and silty soils due to the challenges in the transport of bacteria cells (Behzadipour et al. 2020; Hataf and Jamali 2018; Islam Md et al. 2020; Soon et al. 2014), it can still mitigate rainfall-induced erosion on these types of slopes. Successful applications include collapsing gully slopes (Lu et al. 2021), loess slopes (Cheng et al. 2021; Sun et al. 2022), granite residual soil slopes (Wang et al. 2023), and clayey slopes with varying sand contents (Cheng et al. 2021). However, as the particle size of slope soils decreased, the performance of MICP reduced significantly. For example, compared to the results of Sun et al. (2021c) as stated previously, when MICP was applied to granite residual soil with a mean particle size of 96 µm, the efficiency in mitigating rainfall-induced erosion was markedly better, with the erosion rate decreasing by more than 90% (Wang et al. 2023).

Uniformity of biotreatment on field slopes

However, it is important to note that the studies mentioned earlier were primarily conducted using model tests. In the field, erosion mitigation typically involves large areas. In addition, the artificial spraying method is commonly used for treating slope surfaces (Liu et al. 2021b; Meng et al. 2021; Sun et al. 2021a; Xiao et al. 2022b). The arbitrary nature of artificial spraying makes the uniformity of the treatment a crucial concern. To date, only a few in-situ works have been conducted to assess the performance of biocementation in protecting slope soils from rainfall-induced erosion. For example, Sun et al. (2021c) evaluated the effectiveness of EICP in protecting dust soil slopes from rainfall-induced erosion in a quarry. Although positive results were obtained, the information from these in-situ tests was limited. A more detailed field-scale study was later conducted by Xiao et al. (2022b), which involved the design of a bio-spray system, an artificial rainfall system, and an effluent slurry collection system. These systems allowed for a quantitative investigation of erosion caused by artificial rainfall on clayey slopes. Although MICP treatment reduced erosion intensity, the erosion of the slope was not consistently related to the levels of cementation. In fact, the slope treated with 12 cycles of MICP showed more serious erosion than the slope treated with 6 cycles, based on visual observations. Gullies formed on the slope surface, likely due to enhanced surface runoff and non-uniform cementation (Xiao et al. 2022a). Following the work by Xiao et al. (2022b), we further investigated the erosion characteristics caused by natural rainfall at the same location. It appears that the erosion resistance of MICP-treated slopes under natural rainfall was better than that under artificial rainfall. In Xiao et al. (2022b), with a total accumulated precipitation of about 525 mm, all slopes showed significant erosion, whereas even the untreated slope in our study did not exhibit obvious erosion after similar accumulated precipitation. The difference is likely due to the much stronger artificial rainfall intensity used in the earlier study, which generated higher shear forces that are rarely encountered under natural conditions (Cheng et al. 2021). Therefore, we can conclude that the erosion characteristics observed under artificial rainfall conditions may not fully represent those under real-world conditions. However, similar to the findings of Xiao et al. (2022b), erosion on the slope surface was not uniform, as evidenced by the 3D scanning results for all three slopes (Fig. 8), with uneroded and eroded areas randomly distributed across the slope surfaces.

Durability of biotreatment on field slopes

As erosion control in the field involves a long period, the durability of MICP is another key concern. However, there have been only a few studies focused on the long-term durability of MICP for surface protection. For example, Li et al. (2019) conducted a long-term field test in the Ulan Buh Desert to manage wind-induced erosion of sand particles using MICP. They observed that after a whole freeze-thaw cycle, i.e., 210 days of exposure to the natural environment, part of the surficial crust was broken. Later, Meng et al. (2021) also conducted field tests in the Ulan Buh Desert to examine the effectiveness of MICP in mitigating wind erosion. In these tests, the performance of the MICP treatment was assessed by measuring erosion depth and bearing capacity. They found that the bearing capacity of the treated sand decreased and the erosion depth increased over time, indicating that the cementation deteriorated with time. More recently, Ji et al. (2024) conducted field tests to evaluate the long-term performance of MICP in drought mitigation. They found that calcium carbonate content decreased significantly after 16 months of exposure due to the deterioration of the surface crust caused by wet-dry and freeze-thaw cycles in natural environments. Similarly, the current work showed that the long-term durability of MICP-treated slope surfaces was not particularly strong, as the erosion rate increased and the weakly cemented slope eventually collapsed after a certain period of erosion.

From the above discussion, it can be concluded that while the feasibility of MICP for erosion control on slopes of different soil types and gradations has been widely investigated, future research and engineering efforts should focus on designing more sophisticated equipment or improving stabilization methods. These advancements are necessary to ensure the uniformity of MICP treatment and to enhance its long-term durability.

Conclusions

In this study, we applied MICP to mitigate rainfall-induced erosion on gravelly clay slopes at a construction site in Longyan, Fujian, China. The slopes were stabilized using the spraying method, and we examined the performance of MICP under natural rainfall conditions over a relatively long period, from September 2012 to January 2022. In addition, photos of the slope were taken until September 2022. Our findings indicate that MICP can effectively mitigate rainfall-induced erosion in a short period. The amount of accumulated eroded soils from the biocemented slopes were less than those from the untreated slope and tended to decrease as cementation levels increased. Similarly, surface strength also improved with higher cementation levels. In addition, the scanning of the slope surfaces revealed that surface erosion was most severe on the untreated slope. Although the efficiency of MICP in mitigating erosion on gravelly clay slopes was lower compared to that on sandy slopes, the MICP method still provided protection against erosion and collapse when the cementation levels were relatively high. An additional exciting finding was the natural growth of grass on the heavily cemented slope, suggesting that MICP is not only an effective soil stabilization method but also an eco-friendly one. However, it should be noted that issues related to uniformity and long-term durability still require careful attention and improvement in future applications.

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Data availability The datasets generated during and analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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