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Mudassir Mehmood, Wen Nie, Jiewang Gao, Yunlong Liu, Fahad Alshawmar & Bantayehu Uba Uge

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Sustainable Stabilization of Expansive Soils for Slope Applications Using Enzyme-Induced Carbonate Precipitation and Iron Ore Tailings

Mudassir Mehmood
a) State Key Laboratory of Metal Mining Safety and Disaster Prevention and Control, Maanshan, Anhui 243000, China
b) School of Resources and Safety Engineering, Chongqing University, Chongqing 400044, China
Email: Mudassirktk@hotmail.com
Wen Nie *
a) State Key Laboratory of Metal Mining Safety and Disaster Prevention and Control, Maanshan Anhui 243000, China
b) School of Resources and Safety Engineering, Chongqing University, Chongqing 400044, China
Email: Wen.nie@vip.tom.com
Jiewang Gao
a) State Key Laboratory of Metal Mining Safety and Disaster Prevention and Control, Maanshan, Anhui 243000, China
Email: 1374539571@qq.com
Yunlong Liu
c) School of Civil Engineering, Zhengzhou University, Zhengzhou 450001, China
Email: liuyunlong@gs.zzu.edu.cn
Fahad Alshawmar *
d) Department of Civil Engineering, College of Engineering, Qassim University, Buraydah 51452, Saudi Arabia
Email: shomr@qu.edu.sa
Bantayehu Uba Uge
e) Faculty of Civil Engineering & Built Environment, Hawassa University, Hawassa, Ethiopia
Email: ubabanti@gmail.com
*Corresponding authors: **Fahad Alshawmar (shomr@qu.edu.sa) & Wen Nie (Wen.nie@vip.tom.com)**

Abstract

Expansive soils exhibit pronounced swelling-shrinkage behavior, low shear strength, and high moisture sensitivity, posing significant challenges to the stability of geotechnical structures such as embankments and tailings dam slopes. In this study, a sustainable stabilization strategy integrating enzyme-induced carbonate precipitation (EICP) with iron ore tailings is investigated to improve the hydro-mechanical performance of expansive soils. A comprehensive experimental program was conducted to evaluate changes in unconfined compressive strength (UCS), swelling pressure (P_s), hydraulic conductivity (K_s), cohesion (c), and internal friction angle (φ). Microstructural characterization using scanning electron microscopy and X-ray diffraction was performed to examine calcium carbonate precipitation and its cementation effects within the soil matrix. The results demonstrate that the combined EICP-iron ore tailings treatment significantly enhances soil performance, with UCS, c, and φ increasing by approximately 113%, 48%, and 98%, respectively, while P_s and K_s decrease by approximately 98% and 69%. Furthermore, seepage and slope stability analysis using GeoStudio

(SEEP/W and SLOPE/W) indicate that the stabilized soil achieves a markedly higher factor of safety (FoS = 1.896) compared to untreated soils. The findings confirm that the synergistic integration of EICP and iron ore tailings provides an effective, environmentally sustainable, and engineering-feasible solution for stabilizing expansive soils and improving slope performance in tailings dam applications.

Keywords: Expansive soil; Stabilization; Sustainability; Particle size; Slope stability; Microscopic structure

1 Introduction

The rapid growth of mining and infrastructure projects has increased the need for reliable and sustainable slope stabilization techniques, especially in the construction and maintenance of tailings dams [1]. These earth structures, often constructed using locally available soils and industrial byproducts, need to endure a range of geotechnical issues, such as shear failure, seepage, and settlement [2, 3]. In many regions, a major issue is the existence of expansive soils, which are extremely sensitive to moisture fluctuations [4, 5]. Their tendency to swell and dry upon wetting and drying cycles can lead to notable volumetric changes, inducing cracking, heaving, and a reduction in structural integrity[6]. Such behavior, when applied in the construction of slopes or embankments, can compromise long-term stability and safety [7, 8].

Expansive soils, classified as high plasticity clays (CH) in the Unified Soil Classification (USCS) System, contain montmorillonite minerals, which contribute to their significant potential for swelling and shrinking [9]. Although expansive soils typically exhibit low permeability, their high swelling potential and low mechanical strength significantly limit their performance and stability in geotechnical applications [10, 11]. To address these deficiencies, it is necessary to implement strategies aimed at enhancing physical, mechanical, and microscopic properties [12-14].

Traditional methods for enhancing expansive soils involve chemical stabilization using cement, lime, or fly ash [15, 16]. Additionally, Recent studies have explored a wide range of alternative additives to enhance the engineering behavior of expansive soils. Table 1 shows the representative advancements in expansive soil stabilization. However, despite their technical effectiveness, these approaches are associated with considerable environmental drawbacks, such as greenhouse gas emissions and excessive consumption of natural resources, which limit their sustainability [17, 18].

Table 1. Recent advancements in stabilizing expansive soils

Reference	Material Type	Additives	Results
[19]	Expansive	Lime and	↑ UCS, *c*, φ, and ↓ in swell

	soil	Lignosulphonate	potential, Free Swell index, and PI
[20]	Expansive soil	Low-carbon limestone calcined clay cement	↑ UCS, electric conductivity, and ↓ in P*s*
[21]	Expansive soil	Rice husk ash	↑ OMC, φ, and ↓ γd max and Ps
[22]	Expansive soil	Waste marble dust	↑ CBR, γd max, and ↓ swell potential, and OMC
[5]	Expansive soil	Eggshell powder	↑ CBR, UCS, and ↓ swelling pressure
[23]	Expansive soil	Fly ash	↑ UCS and ↓ PI, swell pressure, and swell potential
[24]	Expansive soil	Cement kiln dust	↑ UCS and OMC and ↓ γd max
[25]	Expansive soil	Soda lime glass powder	↑ UCS, CBR, γd max, and ↓ PI, OMC
[26]	Expansive soil	Titanium gypsum	↑ UCS, *c*, φ, and ↓ in PI, swell potential, and compression index
[27]	Expansive soil	Polypropylene fibers	↑ CBR, UCS, and ↓ in free swell and P*s*

Note: Cohesion (*c*), Internal friction angle (φ), Unconfined compressive strength (UCS), Swelling pressure (P*s*), California bearing ratio (CBR), Optimum moisture content (OMC)

Therefore, the growing focus on sustainability within geotechnical engineering has led researchers to investigate alternative, environmentally friendly approaches for soil stabilization [28, 29]. Among these, bio-geotechnical techniques such as Enzyme-Induced Carbonate Precipitation (EICP) and Microbially Induced Carbonate Precipitation (MICP) have gained interest, especially EICP, a bioinspired technique that promotes calcium carbonate formation within the soil matrix to enhance soil characteristics [30, 31]. EICP employs urease enzymes, typically derived from natural sources like soybean or jack bean meal, to facilitate the breakdown of urea into ammonium and carbonate ions. When calcium ions are added, they interact with the carbonate to produce calcium carbonate ($CaCO_3$), which helps to bind soil particles together, enhancing strength and decreasing permeability [32]. EICP presents several benefits over MICP, including a quicker reaction time, enhanced control over the conditions of the reaction, and the capability to operate without relying on bacterial activity, which can be sensitive to environmental conditions [33, 34].

In recent years, numerous studies have highlighted the success of EICP in enhancing various problematic soils [35, 36]. Previous studies have demonstrated the potential of bio-cementation to enhance soil mechanical properties. For instance, Ghasemi et al. (2022) reported, through molecular dynamics simulations and laboratory experiments, a notable improvement in mechanical behavior due to bio-cementation [37]. Liu et al. (2025) emphasized that EICP treatment considerably increases the soil-water retention capacity and decreases permeability in expansive soils [38]. These advancements have significant implications for use in slopes and embankments, where both strength and resistance to water infiltration are essential.

Additionally, industrial byproducts such as iron ore tailings have been investigated as materials for enhancing soil due to their accessibility, affordability, and favorable physical characteristics. These tailings are fine-grained and often contain minerals such as Fe_2O_3, SiO_2, and CaO, which can contribute to soil densification and chemical activity [39]. Osinubi et al. (2015) indicate that adding iron ore tailings to clayey soils improves compaction and strength properties while decreasing plasticity [8].

The integration of EICP with iron ore tailings offers an innovative and sustainable approach to expansive soil stabilization. The tailings materials aid in the mechanical densification of the soil, while EICP facilitates calcium carbonate precipitation, effectively binding the soil particles. This synergistic mechanism not only enhances the strength and durability of the treated soil but also helps in reducing permeability and swell potential, making it particularly effective for civil engineering structures.

Moreover, in geotechnical engineering practice, the ultimate performance of stabilized soils is not solely governed by improvements observed at the material level but by their ability to enhance the stability of full-scale earth structures such as slopes, embankments, and tailings dams. Particularly, for expansive soils, slope stability is strongly influenced by coupled hydro-mechanical processes, including moisture infiltration, suction loss, and strength degradation during wetting-drying cycles [13]. Therefore, evaluating stabilization techniques exclusively through laboratory strength or swelling tests may not adequately reflect their effectiveness under field-relevant conditions.

Furthermore, Slope stability is commonly quantified using the factor of safety, which represents the balance between resisting and driving forces along potential failure surfaces [40]. Conventional limit equilibrium methods (LEMs), such as Bishop, Janbu, and Morgenstern Price, remain widely used due to their simplicity and computational efficiency [41]. However, these methods are limited in their ability to capture spatial variations in pore-water pressure, unsaturated flow behavior, and material heterogeneity factors that are particularly critical for expansive soils subjected to seepage and rainfall infiltration. In contrast, finite element-based approaches, such as those implemented in GeoStudio’s SEEP/W and SLOPE/W modules, allow for the coupled simulation of seepage and mechanical stability, enabling a more realistic representation of slope behavior under variable hydraulic conditions [42].

Recent studies have begun to recognize the importance of integrating soil improvement techniques with numerical slope stability analysis. For instance, Rajak et al. (2018) found that an optimum fly ash content significantly increases the slope factor of safety (FoS) and resistance to instability, while Gowthaman et al. (2022) concluded that bio-mediated treatments have been shown to improve the resilience of slope soils under cyclic wetting and drying conditions [43]. Despite these advances, existing studies have primarily focused on either mechanical reinforcement or bio-treatment in isolation and have largely relied on idealized soil parameters or simplified geometries. However, the application of EICP in slope-scale analysis, particularly in expansive soils and in combination with industrial byproducts, remains largely unexplored.

To address this research gap, the present study proposes an integrated experimental and numerical approach for evaluating the effectiveness of EICP and iron ore tailings, treated expansive soil in slope applications. Laboratory tests are conducted to quantify changes in physical, mechanical, and microstructural properties resulting from the combined treatment. These experimentally derived parameters are then incorporated directly into coupled seepage and slope stability models using SEEP/W and SLOPE/W. A real tailings-dam geometry from Ma’anshan, China, is employed to assess the influence of soil treatment on pore-water pressure distribution and the factor of safety under realistic boundary conditions.

The novelty of this study lies in (i) the synergistic use of EICP and iron ore tailings for expansive soil stabilization, (ii) the explicit coupling of laboratory-scale bio-cementation effects with slope-scale numerical modeling, and (iii) the evaluation of hydro-mechanical performance under conditions relevant to tailings dams and moisture-sensitive slopes. By bridging the gap between material improvements and structural stability, this research provides a scientifically rigorous, environmentally sustainable framework for slope stabilization in mining and infrastructure projects.

2 Experimental materials and methods

2.1 Materials and their properties

The materials used in this study were expansive soil, soybeans, calcium chloride, urea, and iron ore. The expansive soil was sourced from a railway line project site in Nanyang City, Henan, at a depth of 1.5 to 2 meters (Figure 1a), and Iron ore was procured from the upstream tailing dam of Maanshan, Anhui (Figure 1b). The basic engineering properties of the natural expansive soil were determined through standard laboratory tests in accordance with relevant ASTM specifications, as described in Section 2.3. The obtained results are summarized in Table 2. The gradation curves of the expansive soil and iron ore tailings are presented in Figure 1c, while Table 3 provides the chemical compositions of both materials.

Table 2. Engineering properties of natural expansive soil

Properties	Obtained value	Standard codes
Unified Soil Classification	CH	ASTM-D2487 [44], ASTM-D7928 [45]
PI	45.3 (%)	ASTM-D4318 [46]
MDD	15.78 (kN/m^3)	ASTM-D698 [47]
Swelling pressure	250 (kPa)	ASTM-D4546 [48]
Optimum moisture content	22.3 (%)	ASTM-D698 [47]
UCS	174 (kPa)	ASTM-D2166 [49]
Cohesion	93.5 (kPa)	ASTM-D3080 [50]
Friction angle	8.08° (φ)	
Permeability	1.55 × 10^{-11} m/s	ASTM-D5084 [51]

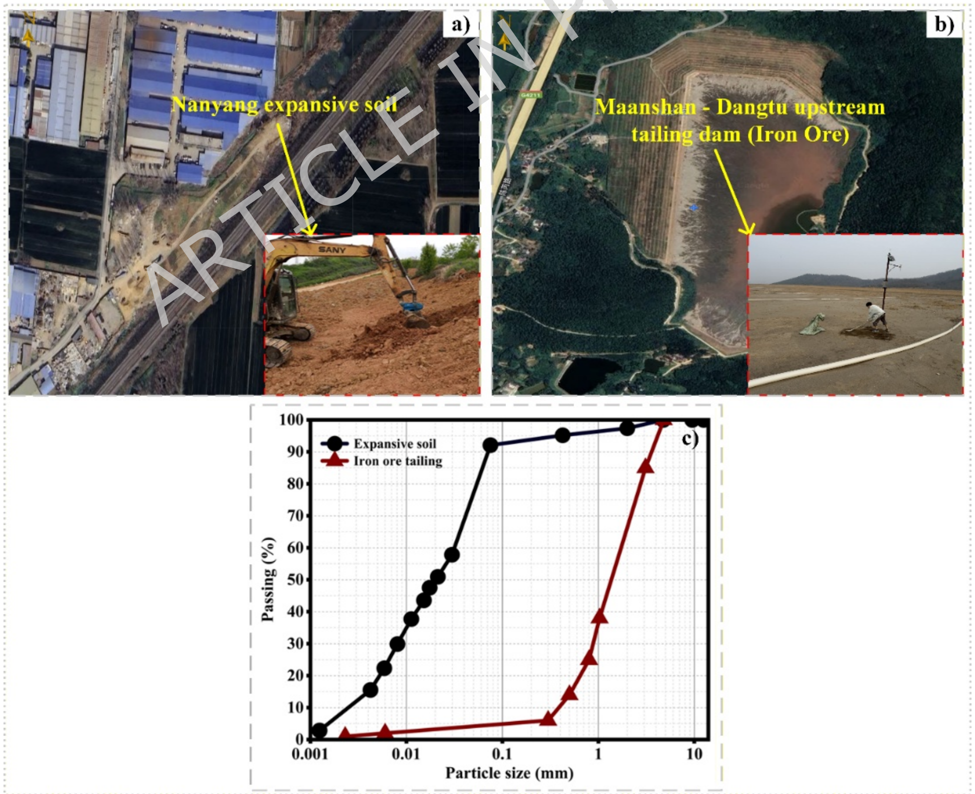

Figure 1. Sampling collection of a) expansive soil, b) iron ore tailings, and c) Sieve analysis of expansive soil and iron ore tailings

Table 3. Chemical composition of expansive soil and iron ore tailings

Chemical Composition	Natural Soil	Iron Ore Tailings
SiO_2	68.9 (%)	62.6 (%)
Al_2O_3	15.5 (%)	7.1 (%)
Fe_2O_3	2.7 (%)	17.5 (%)
MgO	2.8 (%)	3.8 (%)
Al_2O_3	15.5 (%)	7.1 (%)
CaO	5.2 (%)	2.5 (%)
Na_2O	2.1 (%)	1.6 (%)
Others	2.8 (%)	4.6 (%)

2.2 EICP solution preparation and soil mixing procedure

The procedure of EICP solution preparation consists of three basic steps: (1) preparation of the urease solution, (2) preparation of the reaction solution, and (3) EICP solution mixing with the soil sample.

Step 1:

The soybeans used in this study were obtained from the commercial market, China. While commercial soybeans were used due to their high urease activity and availability, their use at large scale may raise sustainability concerns. Before use, the soybeans were dried for 6 hours and then finely powdered. To achieve a urease concentration of 100 g/l, soybean powder was combined with deionized water at a solid-to-liquid ratio of 1:10. The mixture was vigorously stirred for half an hour and subsequently subjected to centrifugation at 3500 rpm for 20 minutes. The soybean urease solution was obtained from the supernatant and kept at 4°C to ensure the enzyme's stability [32].

Step 2:

The reaction mixture was composed of calcium chloride ($CaCl_2$) and urea in equal parts 1:1, with an ideal concentration of 0.75 mol/L and a pH level of 8 [34]. The final mixture was created by adding the urease solution to the reaction solution. To ensure maximum enzyme activity, this step would be performed 1-2 days after the urease solution was prepared, as the activity of soybean-derived urease degraded with time. The complete EICP solution preparation is depicted in Figure 2.

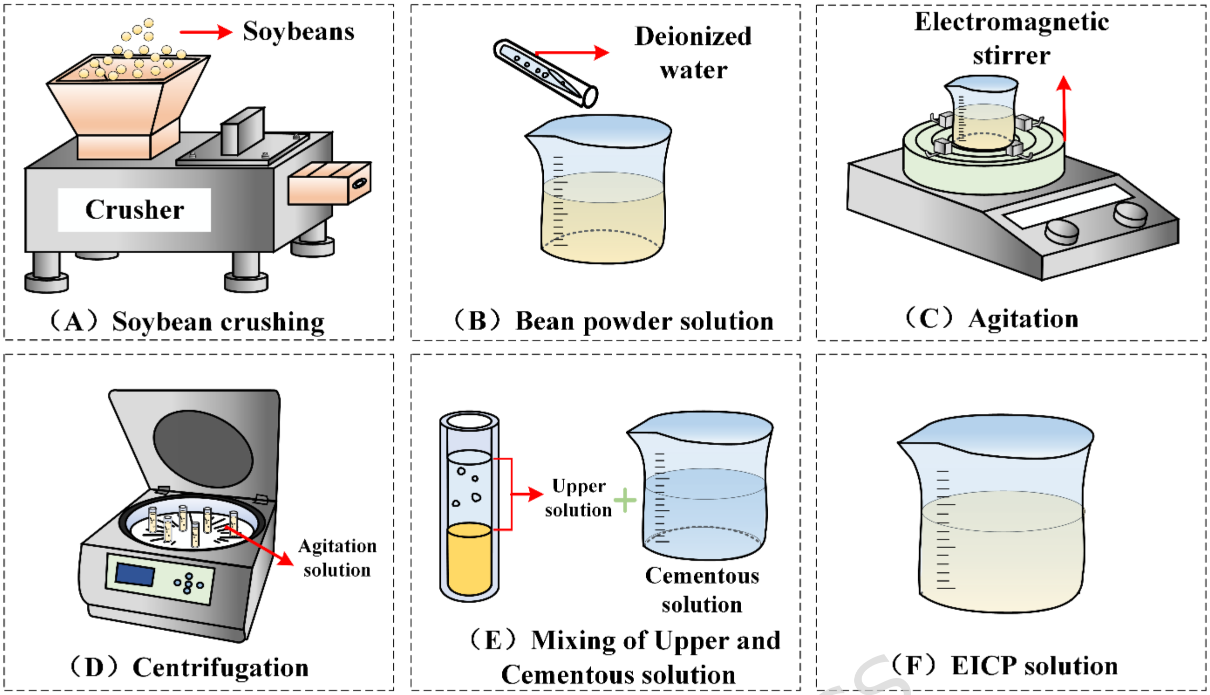

Figure 2. EICP solution preparation

Step 3:

The soil collected from the site was air-dried, mechanically crushed, and sieved to meet the experimental requirements. The natural soil was then mixed with iron ore tailings at 0%, 3%, 6%, 9%, and 12% by weight. The dosage of the EICP solution was determined based on the target OMC of each soil mixture, and the required total liquid content was calculated from the dry mass of the soil mixture. This liquid content was supplied entirely by the mixed EICP solution, prepared by combining the urease solution and reaction solution at a 1:1 volume ratio. No additional deionized water was introduced separately; therefore, the EICP solution fully replaced the conventional mixing water while maintaining the target moisture content corresponding to the OMC. The mixed solution was gradually introduced into the soil matrix during mechanical mixing to ensure uniform distribution of the cementation reagents. This direct mixing method was adopted because the low permeability of expansive soil may limit the effectiveness of injection-based treatment and hinder homogeneous EICP distribution within compacted specimens.

2.3 Experimental setup

Following the determination of the basic engineering properties of the expansive soils and iron ore tailings, the materials were air-dried and their particle size distribution analyzed using sieve analysis ASTM D2487 [44] and hydrometer analysis ASTM D7928 [45]. The prepared soil mixtures were thoroughly homogenized prior to compaction testing. Standard Proctor compaction tests ASTM D698 [47] were conducted to determine the OMC and maximum dry density (MDD) at standard energy levels.

Swelling pressure was measured in accordance with ASTM D4546 [48]. Specimens, statically compacted to a height of approximately 20 mm and a diameter of 61.8 mm, were placed in an oedometer assembly, submerged under a seating load of ~5 kPa, and allowed to swell until equilibrium on a logarithmic time scale. The swelling pressure was determined by incrementally loading the specimen until its void ratio returned to the pre-swelling value.

UCS tests were performed following ASTM D2166 [49]. Cylindrical specimens 38 mm diameter × 76 mm height were statically compacted in three layers with interlayer scoring to ensure bonding. Samples were cured at 25 °C for 3 to 28 days, wrapped in plastic to prevent moisture loss. Tests were conducted at a constant strain rate corresponding to 10% axial deformation, recording load (N) and displacement (mm).

Direct shear tests were carried out in accordance with ASTM D3080 [50] on specimens prepared at OMC and MDD, with dimensions of 61.8 mm diameter × 20 mm height. Shear force was applied at a rate of 0.01 mm/min under normal stresses ranging from 100 to 400 kPa. It should be noted that the direct shear test results are primarily used for comparative evaluation of shear strength improvement between untreated and treated soils. Although the method has limitations for fully saturated clay, the derived parameters are considered suitable for preliminary stability assessment within the Mohr-Coulomb framework.

The hydraulic conductivity of the prepared soil specimens was evaluated using the falling-head permeability approach in accordance with ASTM D5084 [51]. Prior to testing, the specimens were statically compacted to their respective MDD and OMC within a specially fabricated mold measuring 6.18 cm in diameter and 4.0 cm in height. Porous stones in combination with filter papers were installed at the top and bottom boundaries of the specimen to facilitate uniform flow conditions. To prevent preferential flow paths along the specimen-mold interface, the internal mold surfaces were sealed using high-vacuum silicone grease. Following full saturation, a stable flow regime was established by applying a controlled hydraulic gradient, and the coefficient of permeability (k) was continuously monitored until consistent readings were obtained, ensuring the reliability and accuracy of the measured values. It is important to note that all test specimens were prepared at their respective OMC and MDD, ensuring consistency and reproducibility across all experimental procedures. Microstructural investigations of Natural and stabilized soil samples were conducted using scanning electron microscopy (SEM) with a Quanta™ 250 field-emission gun microscope operated at 30 kV. The specimens were oven-dried at 40 °C for 24 h, mounted on aluminum stubs, and examined at varying magnifications to assess changes in particle morphology, pore structure, and cementitious bonding within the treated soil matrix. Additionally, X-ray diffraction (XRD) analysis was performed to identify and compare the mineralogical composition of the natural and modified expansive soils.

2.4 Numerical analysis

In this study, the real-world geometry and material parameters of the Ma'anshan, Dangtu, tailings dam were used as a representative case study. The model serves as a baseline to evaluate and compare the effects of natural expansive soil, stabilized soil with EICP, and a synergic combination of expansive soil, EICP, and iron ore tailings on pore pressure distribution and slope stability.

2.4.1 Computational Method

The Geo-Studio software is utilized to simulate and calculate the stability of tailing dams under various rock-soil materials. As a professional, efficient, and powerful finite element simulation tool, Geo-Studio is primarily used for geotechnical engineering and environmental engineering simulations. It features eight specialized sub-modules tailored for different engineering fields, including solid mechanics, fluid dynamics, and pollutant migration. These modules can be coupled with each other to address practical engineering challenges, which explains their widespread application in geotechnical engineering.

The stability analysis of this tailings dam will use the SEEP/W and SLOPE/W modules in Geo-Studio software for coupled calculations. The SEEP/W module is mainly used to calculate the seepage field results within the dam structure, using saturated seepage theory. Then, the seepage field calculation results from the SEEP/W module will be used collaboratively with the SLOPE/W module, which describes the failure behavior of the geotechnical body. Finally, the Bishop method will be used to calculate the FoS under seepage conditions. This evaluation process aims to comprehensively assess the overall stability of the tailings dam.

In this study, a mixing-based treatment approach was considered for the application of EICP and iron ore tailings due to the very low permeability of expansive soils, which restricts the effectiveness of injection-based methods. For field-scale implementation, techniques such as in situ deep mixing, rotary tilling, or controlled blending during dam construction can be employed to achieve a relatively uniform distribution of stabilizing agents within the soil mass. In the numerical simulations, the treated soil was assumed to be homogeneous, with material parameters derived from laboratory-prepared specimens representing uniformly stabilized conditions.

2.4.2 Geometric model and boundary conditions

Based on the geological survey data of the Qingshan tailings pond Ma'anshan, Dangtu, a representative longitudinal cross-section of the tailings pond was obtained (Fig 3). The tailings dam structure includes four core components: i) the initial dam body, ii) the tailings fill dam, iii) the tailings deposition layer, and iv) the bedrock layer. The entire tailings pond has a longitudinal length of 420 meters and a total height of 80 meters, which includes a main dam section 50 meters high. All subsidiary dams are designed with an upstream-to-downstream slope ratio of 1:2, and the crest width of each dam is uniformly maintained at 5 meters. The slope of the tailings deposition beach is 2%.

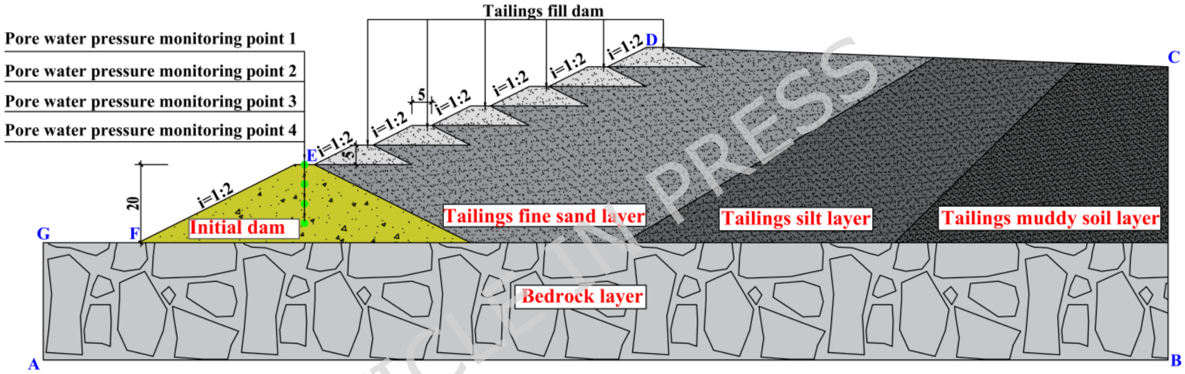

Figure 3. Computational geometric models

To simplify the analysis without affecting the results, the following assumptions were adopted (Fig 3): (1) assuming that the entire initial dam, the embankment dam, and the tailings deposition body are isotropic materials; (2) the bedrock layer was simplified as a uniform stratum; and (3) reducing the size of the calculation model by truncating the geological layers at the reservoir tail, shortening the model from 420 meters to 290 meters.

To analyze the impact of groundwater seepage on slope stability, segment AG was defined as the downstream boundary with a total head of 20 m, while segment BC represents the upstream boundary with a total head of 50 m. These upstream and downstream water levels are clearly illustrated in Figure 3. The water level data were obtained from the engineering survey report. To better investigate the effects of different dam materials on groundwater seepage, four pore pressure monitoring points were strategically placed at intervals of 5m along the initial dam section from top to bottom, totaling four monitoring points in the computational model.

The numerical model was developed using GeoStudio under two-dimensional conditions. The geometry was imported at a 1:1 scale, with a model width of 290 m and heights of 30 m and 75 m on the left and right sides, respectively. A 1 m quadrilateral and triangular mesh division is used, and the model has a total of 18,770 elements and 18,513 nodes.

Table 4. Conditions for Simulations

S.No	Simulated condition	Category
1	Initial dam materials (The initial dam is 20m high)	Iron ore tailings Natural expansive soil Expansive soil+EICP Expansive soil+EICP+iron ore tailings
2	Initial dam height/m (Expansive soil+EICP+iron ore tailings)	20 25 30 35

2.4.3 Simulation Conditions

This simulation scenario comprises two distinct conditions. The first maintains the total tailings dam height at 50m with an initial height of 20m, evaluating stability under four material configurations: iron ore tailings, natural expansive soil, expansive soil with EICP, and expansive soil+EICP+iron ore tailings. The second condition retains the total height at 50m but uses an initial construction material of expansive soil+EICP+iron ore tailings, with stability analysis conducted for initial heights of 20m,25m,30m, and 35m. Detailed simulation parameters are presented in Table 4.

3 Results and discussion

3.1 Selection of iron ore tailings percentage

To determine the optimal percentage of iron ore tailings for expansive soil stabilization, varying proportions (3%, 6%, 9%, and 12%) were incorporated into the expansive soil. After 0 and 3 days of curing, the swelling pressure and UCS of the treated specimens were measured. As shown in Figure 4a, the swelling pressures decreased steadily with increasing iron ore tailings content, indicating a significant stabilizing effect of iron ore tailings. Similarly, Figure 4b shows a corresponding increase in UCS with increasing content of iron ore tailing, further confirming the increase in mechanical strength. Figure 4 highlights the strong relationship between the addition of iron ore tailings and the observed changes in soil behavior. However, Figure 4 indicates that the reduction in swelling pressure and the increase in UCS become marginal at an iron ore tailings content of 12%. Beyond this level, further increases in iron ore content result in minimal improvement in UCS. Accordingly, an iron ore content of 12% was identified as the optimum and selected for subsequent experimental analysis.

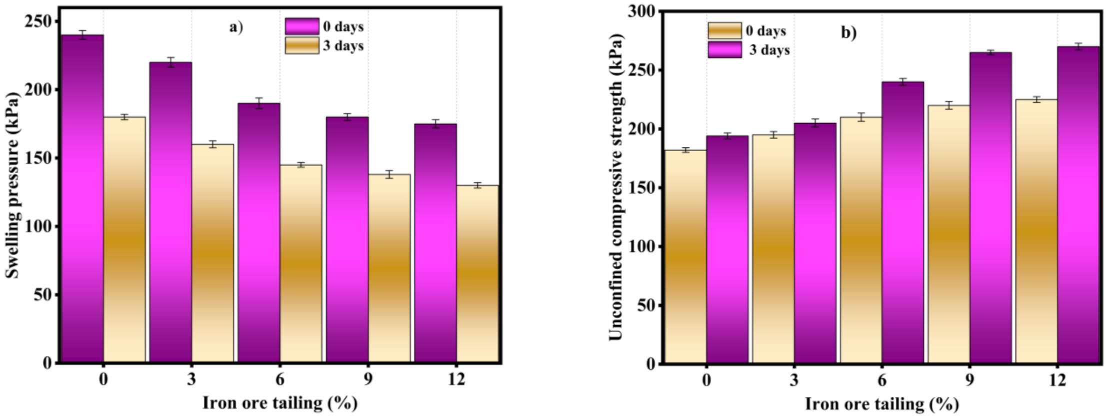

Figure 4. Selection of the iron ore tailing percentage: a) Swelling Pressure, b) UCS

3.2 MDD and OMC

Figure 5a shows the MDD values of natural soil, EICP modified soil, and EICP + iron ore tailing stabilized soil were 15.78 kN/m³, 16.71 kN/m³, and 17.1 kN/m³, respectively. Similarly, the OMC for natural soil is 22.3% and then decreased to 19.85% and 16.7% for the soils treated with EICP and EICP + iron ore tailing, respectively. The increase in the density of EICP-treated soils can be attributed to an ion exchange process in which monovalent sodium ions are replaced by divalent calcium ions. This interaction strengthens the bonds within the crystals, reduces the distance between the silicate layers, and decreases the volume of bound water. As a result, the microstructure of montmorillonite changes from a dispersed layer arrangement to larger, more compact aggregates of clay minerals, resulting in an overall increase in soil density [52].

Moreover, the influence of varying iron ore tailings content on the MDD and OMC of EICP-treated expansive soil is shown in Figure 5b. An increase in MDD was observed after the addition of iron ore to the treated soil matrix. This increase can be attributed to the fine iron ore particles partially filling the voids, resulting in a denser stacking pattern. Furthermore, the specific gravity of iron ore is higher than natural soil particles, resulting in an increase in MDD [39]. In contrast, the OMC decreases with increasing iron ore content, mainly due to the non-plasticity and low water absorption capacity of iron ore tailings. As a result, less water is required to achieve maximum compaction, thus reducing the optimum moisture content while improving the overall compaction properties of the stabilized soil [8].

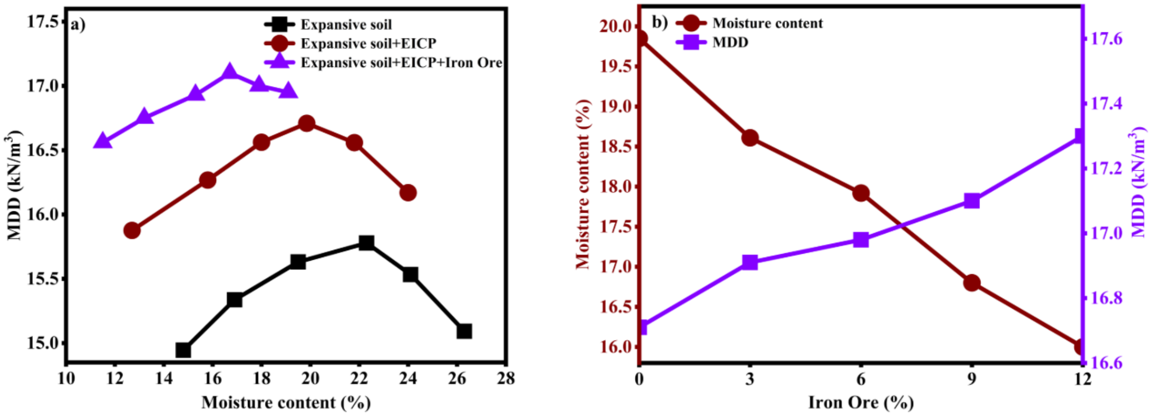

Figure 5: Compaction behavior of treated and untreated soil, a) Maximum dry density versus moisture content, b) Iron ore tailings effects on maximum dry density and moisture content

3.3 Swelling pressure

P*s* is an important property governing the behavior of volume change in natural expansive soils. Therefore, a detailed evaluation of the P*s* was carried out to investigate the efficiency of the proposed binary contributions. Figure 6 shows the P*s* behavior of the natural expansive soil, the EICP stabilized soil, and the EICP-iron ore tailings blended soil. In the EICP stabilized samples, the P*s* decreased significantly from 250 kPa in the untreated soil to 50 kPa after 28 days of curing.

The gradual decrease in swelling pressure is primarily attributed to the increased carbonate precipitation (calcite) formation in the soil matrix caused by the EICP mechanism. Calcite crystals effectively fill soil pores and bind soil particles together, reducing the soil's ability to swell with water [53, 54].

Additionally, incorporating EICP into naturally expansive soil together with iron ore tailings (12%) significantly reduced the P*s* from 250 kPa to 175, 125, 60, 15, and 5 kPa on days 0 to 28 of curing, respectively. The observed exponential decrease in P*s* can be attributed to the stabilization mechanism: iron ore particles fill soil voids, promoting physical densification, while EICP promotes calcium carbonate precipitation and the formation of a bio-cemented film around soil particles. This synergistic effect effectively inhibits moisture-induced expansion, improving the dimensional stability of the treated soil.

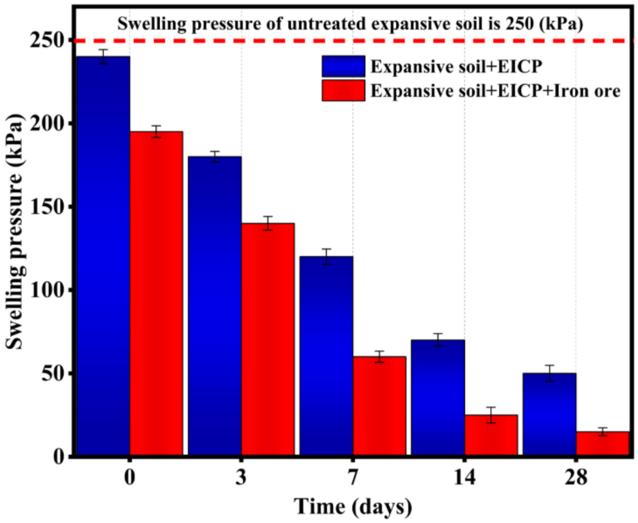

Figure 6: Swelling Pressure vs. time for treated and untreated soil

3.4 Unconfined compressive strength

The UCS test provides substantive insight into the mechanical behavior and structural integrity of soil. Figure 7 illustrates the variation in UCS for natural soil, soil treated with EICP alone, and soil treated with a union of EICP and iron ore tailings, across curing periods of 0-28 days. The UCS of the virgin expansive soil was recorded at 174 kPa. With the addition of EICP, the UCS progressively increased, reaching 289 kPa upon completion of a 28 days curing period. This enhancement can be predominantly ascribed to the calcium carbonate precipitation triggered by the EICP process. The introduction of the enrichment and cementation solutions activated a biochemical reaction pathway that facilitated the nucleation and subsequent growth of calcium carbonate crystals within the soil matrix. These crystals served as effective binding agents, bridging soil particles and enhancing interparticle bonding, thereby significantly improving the strength characteristics of the EICP stabilized soil [55].

It is noteworthy that the combined intrusion of EICP and iron ore tailings further increases the UCS strength from 174 kPa to 220 kPa, 265 kPa, 310 kPa, 340 kPa, and 370 kPa after 0, 3, 7, 14, and 28 days of curing.

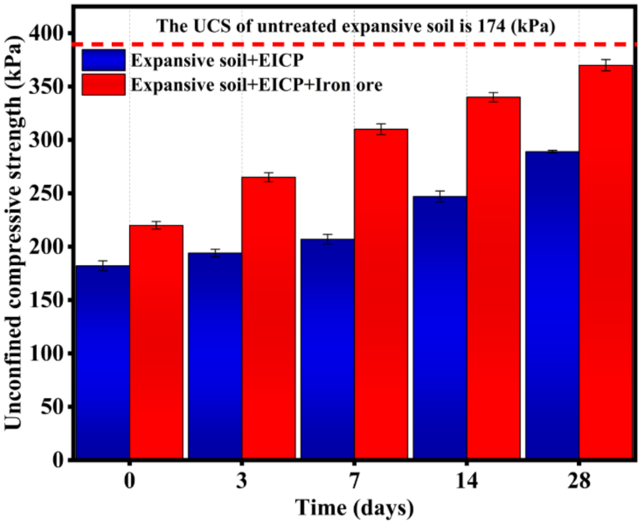

Figure 7: Unconfined compressive strength vs. time for treated and untreated soil

This pronounced strength improvement is governed by a synergistic interaction between the biochemical cementation induced by EICP and the mechanical contribution of the iron ore tailings. From a mechanical perspective, the fine and angular tailings particles enhance soil densification, improve particle interlocking, and increase frictional resistance [39]. Simultaneously, the calcium-bearing phases present in the tailings, as confirmed by the chemical composition in Table 2, provide an internal source of Ca^{2+} ions that complements the externally supplied calcium during EICP treatment. The combined availability of internal and external calcium accelerates calcium carbonate precipitation, promotes stronger interparticle bonding, reduces pore volume, and ultimately leads to the development of a denser and mechanically robust soil skeleton [56].

3.5 Cohesion and Internal Friction Angle

c and φ are key strength parameters affecting the design and performance of geotechnical structures. Figures 8 and 9 illustrate the effect of the EICP process on these two important properties, respectively. The EICP treatment improved the *c* and the φ of the virgin expansive soil. *c* increased from an initial value of 93 kPa to 134 kPa over the 28-day curing period.

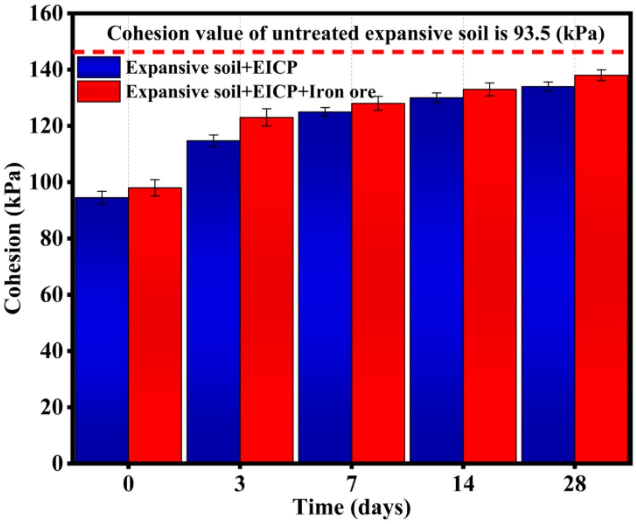

Figure 8: Cohesion vs. time for treated and untreated soil

Similarly, the φ increased from 8.08° to 12.0°. These improvements can be ascribed to the calcium carbonate precipitates formed during the EICP process, which bind soil particles together, reducing particle mobility and thus increasing shear resistance [57].

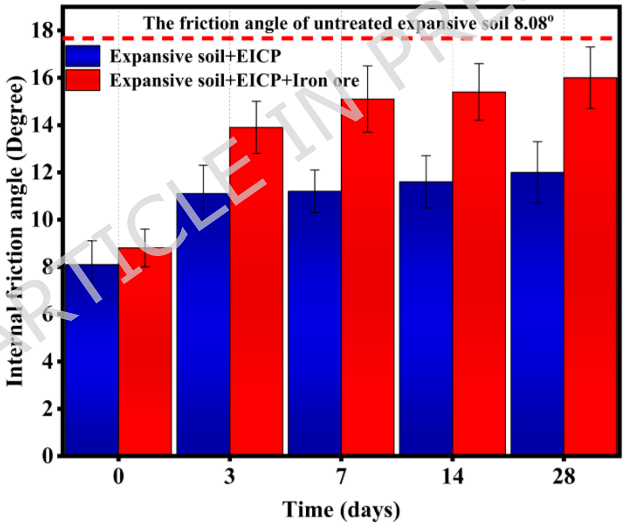

Figure 9: Internal friction angle vs. time for treated and untreated soil

Furthermore, the combined processing of EICP with iron ore tailings showed even more significant effects. *c* values increased 93 to 98, 123, 128, 133, and 138 kPa at 0, 3, 7, 14, and 28 days of curing, respectively, while the internal friction angle increased to 8.08°, 13.9°, 15.1°, 15.4°, and 16°. The improvement in the friction angle may be due to the contribution of iron ore to particle roughness and to the formation of bio-cementation bridges during the EICP process. In addition, biofilm formation on the surfaces of stabilized soil particles during the EICP process may further increase particle adhesion, contributing to the observed increase in cohesive strength [58].

3.6 Permeability

K*s* is the soil's ability to allow water to penetrate and flow through its pore spaces. It is an important parameter for assessing soil hydraulic properties, especially in geotechnical engineering. This property is usually expressed as a permeability coefficient and is influenced by factors such as particle size distribution, soil classification, compaction density, and temperature.

The natural expansive soil tested in this study had a relatively low permeability of 1.55×10^{-11} m/sec. After EICP treatment, the permeability was reduced to 5.77×10^{-12} m/sec, which was mainly due to the precipitation of calcium carbonate in the soil matrix, filling the voids and preventing the flow of pore water[59].

In addition, when the soil was treated with EICP and iron ore tailings, the permeability was further reduced to 4.81×10^{-12}m/sec. This is due to the synergistic effect of the two treatment methods: the fine iron particles and higher specific gravity help to fill the pores, while the calcium carbonate produced by EICP acts as a binder and increases the density of the matrix. These mechanisms work together to significantly reduce soil permeability. These results suggest that the combination of EICP with iron ore not only improves soil strength but also enhances its resistance to water penetration, providing a sustainable solution for stabilizing large areas of soil using industrial byproducts.

3.7 Microstructural characteristics

3.7.1 SEM

The microstructural properties of the treated and untreated soil were investigated using scanning electron microscopy (SEM), as shown in Figures 10a, b, and c. The SEM images showed the presence of dispersed, irregular, angular crystal structures within the clay matrix. These crystals are indicators of calcium carbonate precipitation, which is formed through the EICP process shown in Figure 10b. During the EICP process, calcium carbonate colloids precipitate on the surface of clay particles, forming cementitious bonds that enhance the inter-particle connectivity and structural integrity [37,60]. Furthermore, Figure 10c. shows the cementitious products combined with enzymes that initiate carbonate precipitation, thus stabilizing the clay particles. Moreover, the addition of iron tailings further strengthens the clay particles, helps to form a dense matrix, and enhances the cohesion within the clay structure.

3.7.2 XRD

The presence of calcite in the treated samples was confirmed by semiquantitative analysis using XRD, as shown in Figure 10d. In the XRD spectrum of the EICP-stabilized soil, the intensity of the calcite peak is noticeably higher than that of the natural soil. This enhancement indicates an increase in calcite content due to EICP treatment, which plays an important role in improving the soil's engineering properties. The formation of calcite improves the soil's structural integrity and its resistance to external deformation.

In addition, a slightly sharper calcite peak also appeared in soil stabilized with EICP and iron ore tailings together, highlighting the synergistic effect of bio-cementation and iron ore in promoting calcite precipitation. These results are consistent with the SEM observations, which confirm the presence of calcite in the clay matrix and its reinforcing effect.

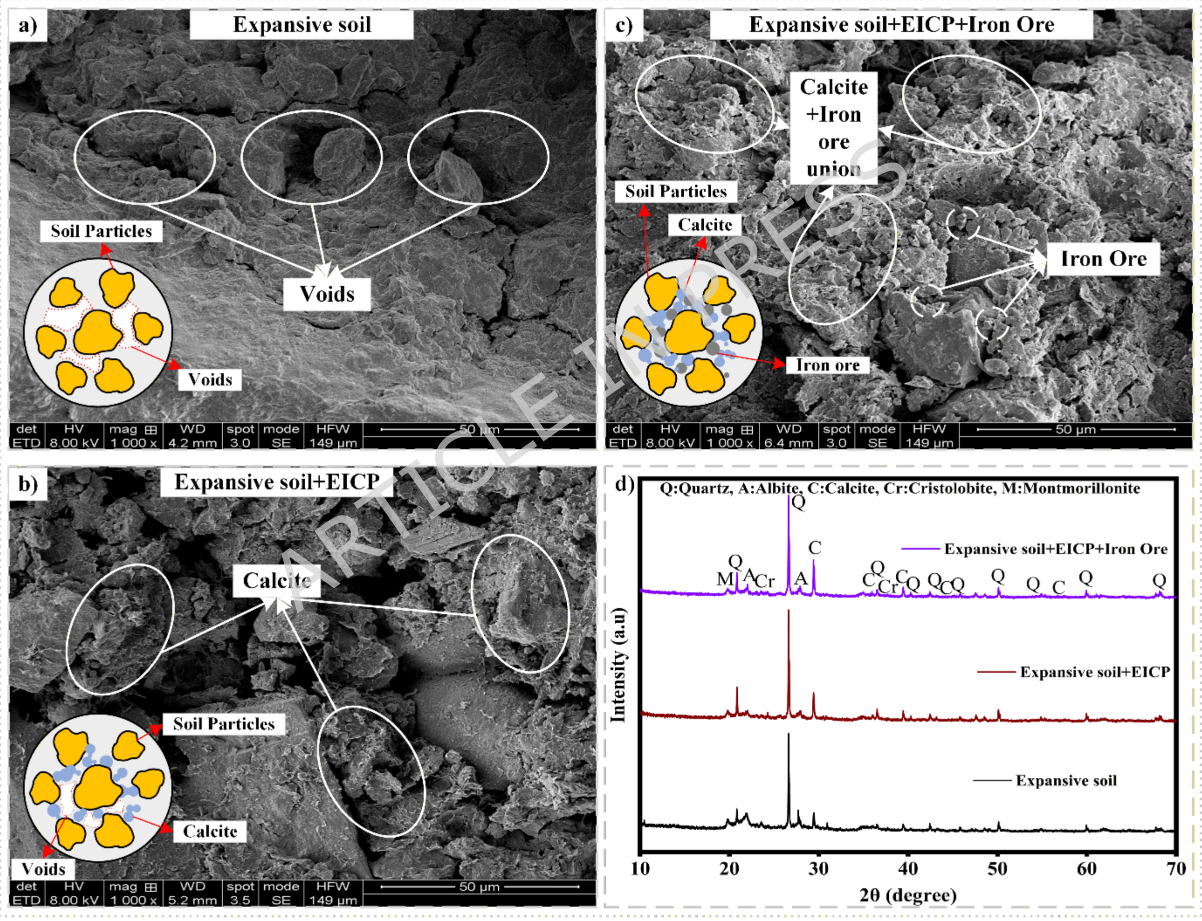

Figure 10: SEM and XRD of untreated and treated soil

4 Numerical analysis

4.1 Material parameter selection

GeoStudio software was utilized for numerical modeling, enabling the integration of geotechnical material parameters within the SEEP/W and SLOPE/W modules. The input parameters adopted in this study are summarized in Table 5 and were selected to realistically represent the mechanical and hydraulic behavior of the initial dam and surrounding geological strata.

The constitutive properties assigned to the dam construction materials, including iron ore tailings, natural soil, EICP-stabilized soil, and expansive soil stabilized through the combined application of EICP and iron ore tailings, were predominantly derived from laboratory-based experimental characterization conducted in this study. In contrast, the parameters associated with the surrounding geological strata were obtained from site-specific geological investigation reports supplied by the enterprise responsible for the upstream tailings dam at Ma’anshan. This combined use of experimentally measured and field-derived parameters ensures that the numerical model accurately reflects both material behavior and in situ geological conditions.

Table 5. Material parameter

Stratum information		Maximum dry density (kN/m^3)	Cohesion （kPa）	Friction angle (°)	Coefficient of permeability （m/sec）	Curing duration (days)
Initial dam materials	Iron Ore	19	8.1	31.1	1.86×10^{-4}	x
	Expansive Soil	15.78	93.5	8.08	1.55×10^{-11}	28
	Expansive Soil+EICP	16.709	134	12	5.77×10^{-12}	28
	Expansive Soil+EICP+Iron Ore	17.1	138	16	4.81×10^{-12}	28
Other geological material parameters	Tailings fill dam	19	8.1	31.1	1.86×10^{-4}	x
	Tailings fine sand layer	18.7	13.1	29	7.59×10^{-5}	x
	Tailings silt layer	19.1	22.8	24.2	2.32×10^{-5}	x
	Tailings muddy soil layer	18.9	21.2	19.7	2.09×10^{-6}	x
	Bedrock layer	19.5	503.5	40.6	3.01×10^{-14}	x

4.2 Analysis and discussions

4.2.1 Seepage analysis

In upstream tailings dam systems, the seepage performance of the initial dam is a critical factor governing structural safety and environmental protection. Inadequate anti-seepage characteristics of the dam material may result in excessive pore water pressure, shallow infiltration lines, and an increased risk of piping and internal erosion. Consequently, the burial depth of the infiltration (phreatic) line is commonly adopted as a key indicator for evaluating seepage stability.

Figure 11 illustrates the simulated seepage fields and pore-water pressure distributions for the initial dam under different material scenarios. When iron ore tailings are considered Figure 11a, the seepage field exhibits a relatively shallow infiltration line and elevated pore-water pressures, indicating high permeability and limited resistance to seepage. In comparison, the use of natural expansive soil Figure 11b results in a downward shift of the infiltration line and a noticeable reduction in pore water pressure, reflecting its lower hydraulic conductivity.

Further improvement is observed for EICP-treated expansive soil Figure 11c, where the seepage contours become more uniform, and the infiltration line is further depressed. This behavior can be attributed to EICP-induced calcium carbonate precipitation, which refines the pore structure and restricts seepage pathways. The most pronounced seepage control is achieved when expansive soil is stabilized using the combined EICP and iron ore tailings approach Figure 11d. In this case, the infiltration line reaches its maximum burial depth, and pore water pressures at all monitoring elevations are consistently minimized, as shown in Figure 11e.

Moreover, the comparative results indicate that the combined EICP-iron ore tailings treatment provides the most effective reduction in seepage and pore water pressure within the initial dam. The synergistic effects of mechanical densification and biochemical cementation significantly enhance the anti-seepage performance of the dam material, thereby improving seepage stability under upstream tailings dam conditions.

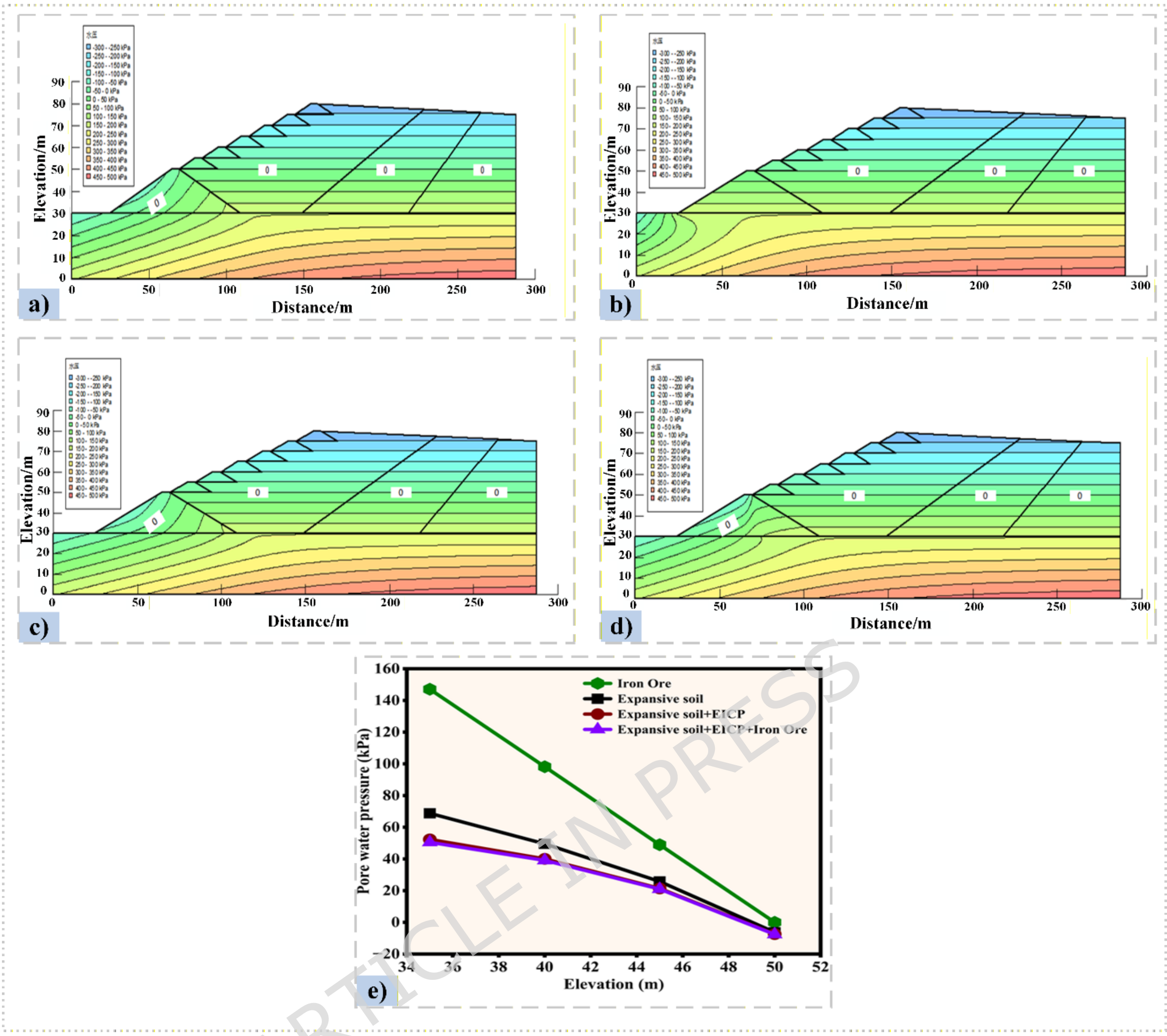

Figure 11: Comparative seepage characteristics and pore pressure evolution under different initial dam materials, a) Seepage field for iron ore, b) Seepage field for expansive soil, c) Seepage field for EICP stabilized soil, d) Seepage field for ECIP and iron ore stabilized soil, and e) Curves of each pore water pressure monitoring point for all material configurations

4.2.2 Early-stage slope stability analysis

Figure 12a-d presents the FoS distributions for the upstream tailings dam slope simulated under different initial dam material scenarios at the early stage, including iron ore tailings, natural expansive soil, EICP-treated soil, and expansive soil stabilized using the combined EICP-iron ore tailings approach. The corresponding calculated FoS values are 1.201, 1.628, 1.807, and 1.896, respectively, indicating a progressive improvement in slope stability with material modification.

When iron ore tailings are considered as the initial dam material Figure 12a, the slope exhibits the lowest FoS, reflecting limited shear resistance and unfavorable hydro-mechanical behavior. Replacing iron ore tailings with natural expansive soil (Figure 12b) results in a marked increase in FoS, primarily due to enhanced cohesion and reduced permeability. Further improvement is achieved through EICP treatment (Figure 12c), which significantly enhances soil strength by promoting calcium carbonate cementation and improving interparticle bonding.

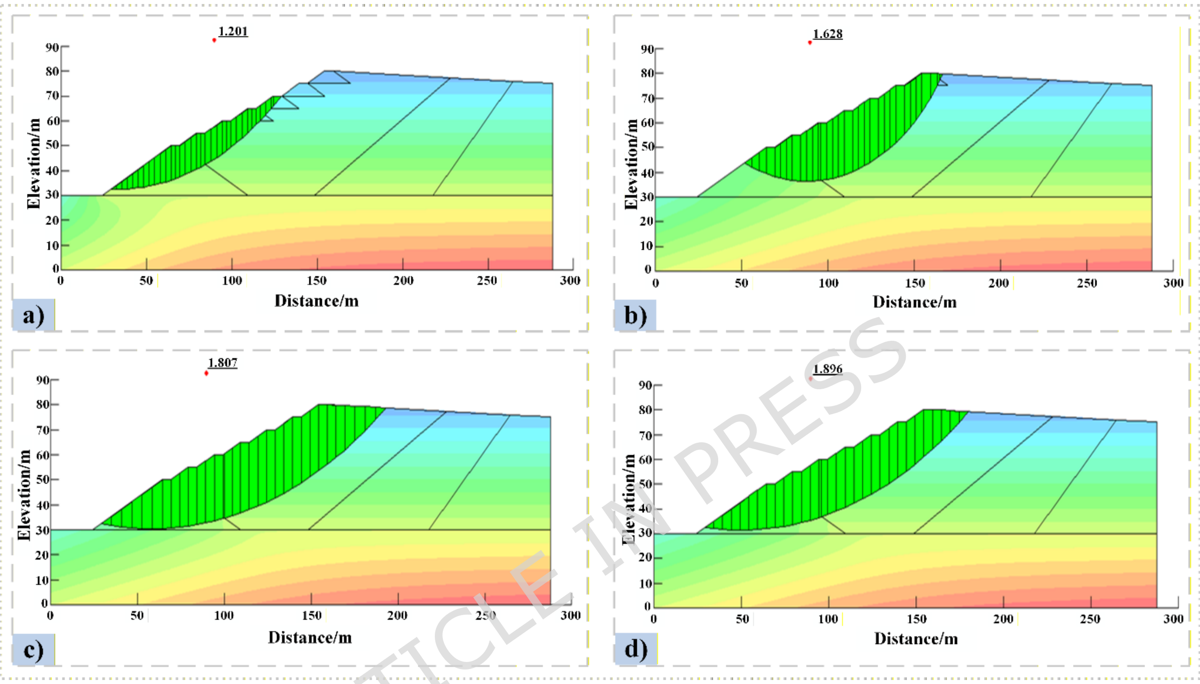

Figure 12: Factor of safety distribution for slopes constructed with different initial dam materials, a) Iron ore, b) Expansive soil, c) Treated soil with EICP, and d) Treated soil with EICP and iron ore

The highest FoS is achieved with the combined EICP and iron ore tailings method for stabilizing expansive soil (Figure 12d). This configuration yields the maximum FoS of 1.896, demonstrating the greatest resistance to slope failure. The superior performance can be attributed to the synergistic interaction between biochemical cementation induced by EICP and mechanical densification and particle interlocking provided by iron ore tailings, which collectively enhance shear strength while mitigating the development of pore water pressure.

Additionally, when considered together with the seepage analysis results, these findings confirm that the combined EICP-iron ore tailings stabilization strategy provides the most effective improvement in both impermeability and slope stability during the early stage of dam development. Consequently, this approach exhibits strong potential for application in the design and optimization of initial dams in upstream tailings pond systems.

4.2.3 Effect of initial dam height on tailings dam stability

Figure 13a-d illustrates the FoS distributions for upstream tailings dam slopes with different initial dam heights (20 m, 25 m, 30 m, and 35 m), considering expansive soil stabilized using the combined EICP-iron ore tailings method as the initial dam material. The corresponding calculated FoS values are 1.896, 2.008, 2.090, and 2.108, respectively, indicating an enhancement in slope stability with increasing initial dam height..

At an initial dam height of 20 m (Figure 13a), the slope exhibits the lowest FoS, reflecting relatively limited resistance to shear deformation during the early construction stage. As the initial dam height increases to 25 m and 30 m (Figure 13b-c), an increase in FoS is observed, suggesting that the combined EICP-iron ore tailings material provides sufficient strength and stiffness to support the additional overburden while maintaining slope stability. Additionally, when the initial dam height reaches 35 m (Figure 13d), the FoS continues to increase, although the rate of improvement becomes less pronounced, indicating a tendency toward stabilization of the safety margin.

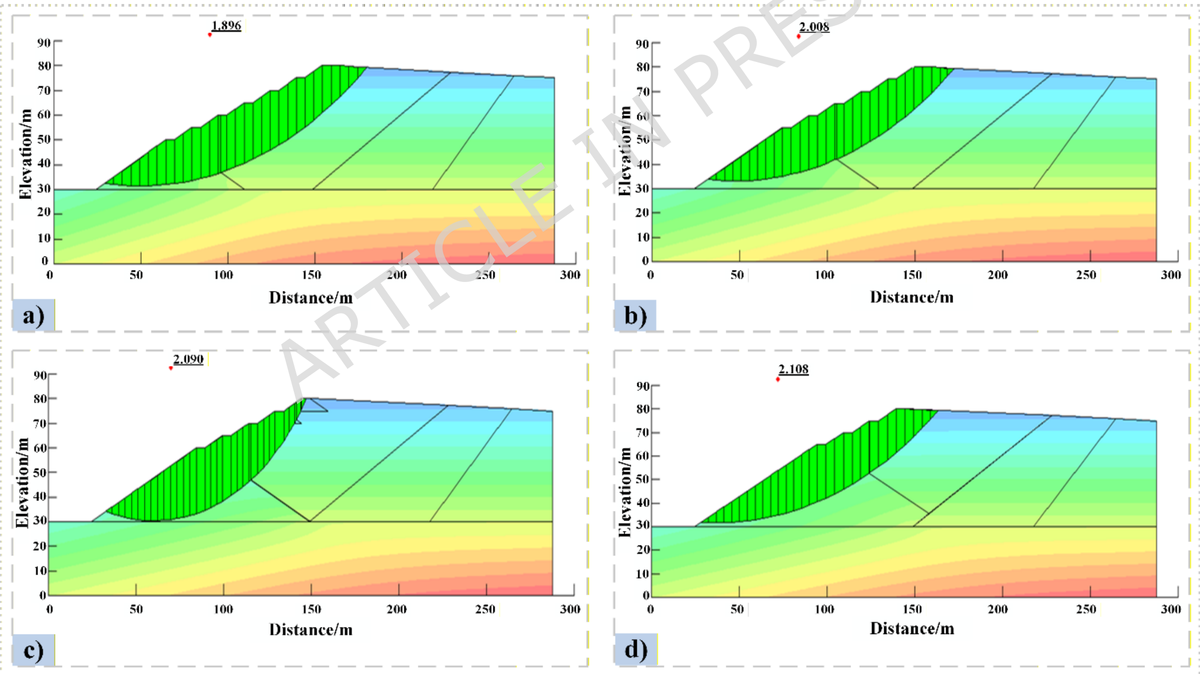

Figure 13: Factor of safety distribution maps for slopes with different initial dam heights: (a) 20 m, (b) 25 m, (c) 30 m, and (d) 35 m.

Moreover, the observed improvement in slope stability with increasing dam height can be attributed to the enhanced confinement effect and improved stress redistribution within the stabilized dam body. The high *c* and frictional resistance of the EICP-iron ore tailings and EICP-stabilized soil enable the slope to accommodate greater self-weight without triggering critical failure mechanisms. These results demonstrate that, within the investigated height range, the use of expansive soil stabilized with combined EICP and iron ore tailings provides adequate stability for higher initial dam configurations. Furthermore, the numerical analysis demonstrates that employing expansive soil stabilized through the combined EICP-iron ore tailings approach as the initial dam material permits an increase in initial dam height without compromising slope safety during the early construction stage. This outcome provides a quantitative, mechanistically supported framework for optimizing initial dam geometry and stabilization strategies in upstream tailings-dam engineering.

5 Conclusions

This study systematically investigated the coupled mechanical, hydraulic, and stability performance of expansive soil stabilized using a combined Enzyme-Induced Carbonate Precipitation (EICP) and iron ore tailings approach, with specific application to slope stability in upstream tailings dam systems. The findings derived from comprehensive laboratory testing and numerical simulations demonstrate the effectiveness of this stabilization strategy in enhancing the hydro-mechanical behavior of expansive soils.

1) The combined incorporation of EICP and iron ore tailings resulted in a substantial enhancement of the unconfined compressive strength peak strength increasing from 174 kPa to 370 kPa after 28 days of curing.
2) Swelling pressure was dramatically reduced from 250 kPa to 5 kPa, reflecting the combined effects of calcium carbonate precipitation and mechanical densification induced by iron ore tailings incorporation.
3) A pronounced reduction in hydraulic conductivity was achieved, with permeability decreasing to 4.81×10^{-12} m/s, indicating significantly improved water resistance and suitability of the treated material for hydraulic barriers and dam core applications.
4) The stabilization treatment led to marked improvements in both cohesion and internal friction angle, thereby enhancing the shear resistance of the soil, which is a critical factor governing slope stability performance.
5) Microstructural analysis using SEM and XRD confirmed the formation of calcium carbonate cementation products and a denser particle arrangement, providing direct evidence of the physicochemical mechanisms underlying the observed macroscopic behavior.
6) Numerical analysis conducted using GeoStudio (SEEP/W and SLOPE/W) demonstrated that expansive soil treated with EICP and an optimum iron ore tailings content of 12% achieved the highest factor of safety (FoS = 1.896), indicating a significant improvement in slope stability relative to untreated and singly treated soil scenarios.

This study provides a novel integrated framework that links laboratory-scale bio-cementation mechanisms with slope-scale numerical stability analysis, thereby bridging the gap between material-level improvement and real engineering performance. From an engineering perspective, the proposed EICP-iron ore tailings approach offers a practical and sustainable alternative for the stabilization of low-permeability expansive soils in large-scale geotechnical applications, particularly in tailings dam construction.

Future Recommendations

Despite the encouraging mechanical, hydraulic, and stability improvements demonstrated through laboratory testing and numerical simulations, it should be recognized that the stabilized soil scenarios evaluated in this study represent idealized performance conditions derived from experimentally calibrated parameters rather than full-scale field implementations. In practice, achieving uniform distribution of treatment agents in low-permeability expansive soils may be challenging; therefore, mixing-based techniques are considered more suitable than injection methods for field application. In addition, the use of commercial-grade soybeans as a urease source may raise sustainability concerns for large-scale applications; thus, alternative sources derived from agricultural waste or byproducts should be explored. Moreover, the numerical analysis was confined to early-stage construction scenarios and did not account for long-term influences such as cyclic wetting-drying, chemical aging, or seismic excitation. Future investigations should therefore emphasize field-scale validation, long-term hydro-mechanical durability, and the optimization of EICP-iron ore tailings treatment strategies under realistic environmental and operational conditions.

Data availability

The data will be made available by the first author upon reasonable request

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Author Contributions

Mudassir Mehmood: Writing original draft, Reviewing, and editing, Conceptualization, Methodology, Investigation, Formal analysis, Data curation. Wen Nie: Reviewing and editing, Funding acquisition, Conceptualization, Supervision. Jiewang Gao: Data curation, Formal Analysis, Software. Yunlong Liu: Conceptualization, Reviewing and editing, Supervision, Fahad Alshawmar: Reviewing, and editing, Funding acquisition. Bantayehu Uba Uge: Data curation, Formal Analysis, Investigation.

Competing Interest

The authors declare no competing interests.