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Sequential Bio-Augmentation for Tropical Peat Stabilization: Synergistic Effects of Granulated Pseudomonas Putida and Bacillus Pasteurii on Shallow Foundation Performance

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ABSTRACT: *Infrastructure development on tropical peatlands faces severe geotechnical constraints due to high organic content and extreme compressibility. This study investigates a novel sequential bio-augmentation approach using encapsulated granules of Pseudomonas putida (for fiber decomposition) and Bacillus pasteurii (for Microbially Induced Calcite Precipitation/MICP) to stabilize tropical peat. The granular formulation was specifically designed to overcome the limitations of traditional liquid suspensions by minimizing moisture addition while maintaining bacterial viability.The bacterial granules were applied at a dosage of 6.75% and cured for 28 days. Laboratory results demonstrated a significant transformation in the peat matrix, characterized by a reduction in fiber content from 50.03% to 20.07% and a decrease in organic matter. These physico-chemical changes led to a substantial increase in soil cohesion, internal friction angle, and stiffness. Integrated numerical modeling using SAP2000 and Plaxis 2D (Mohr-Coulomb model) revealed that the allowable bearing capacity surged by 273%, increasing from 65.40 kN/m² to 243.84 kN/m². Furthermore, vertical settlement was reduced by 48.1% (from 0.02777 m to 0.01440 m). Crucially, the stabilized peat enabled a 45% reduction in foundation dimensions and the total elimination of auxiliary mini-piles required in the untreated state. Compared to existing stabilization benchmarks, this method offers a superior balance between stability and serviceability, providing a robust and sustainable ground improvement strategy for infrastructure on problematic organic soils.*

KEYWORDS - *Peat Stabilization, Sequential Bio-augmentation, MICP, Pseudomonas putida, Bacillus pasteurii, Shallow Foundation.*

I. INTRODUCTION

The rapid expansion of transportation infrastructure in tropical regions, particularly in Indonesia, faces severe geotechnical constraints due to the widespread presence of peatlands. Peat is widely categorized as one of the most problematic geomaterials for engineering due to its extreme organic content (>75%), high moisture levels (up to 600%), and inherently low shear strength [1]. These unique characteristics result in excessive settlement and a high risk of bearing capacity failure, presenting a persistent challenge for the stability and serviceability of shallow foundation systems, such as those used for pedestrian bridges. In the city of Palangka Raya, the prevalence of highly fibrous peat necessitates specialized ground improvement strategies to ensure the long-term integrity of lightweight structures.

Traditional ground improvement techniques, including deep pile foundations, preloading, and chemical stabilization using cement or lime, have been the industry standard for decades [2]. However, these methods are increasingly criticized for their significant environmental footprint and high carbon emissions [2]. Furthermore, the efficacy of chemical stabilizers like cement is often compromised in peat environments; the high acidity and organic matter interfere with the hydration process, leading to inconsistent strength gains. Consequently, there is an urgent global demand for sustainable, "green" geotechnical solutions that can provide reliable soil reinforcement without the environmental costs of conventional binders.

Biological stabilization has recently emerged as a transformative alternative for soil improvement. In particular, Microbially Induced Calcite Precipitation (MICP) has demonstrated success in mineral soils by utilizing ureolytic bacteria to precipitate calcium carbonate ($CaCO_3$), which binds soil particles and enhances structural stiffness [3], [4]. Previous research has also explored the use of Pseudomonas species to accelerate the decomposition of peat fibers [5], thereby improving the physical density of the soil matrix. Despite these promising advancements, a critical gap remains in the practical application of bio-stabilization for peat. Most existing studies rely on liquid bacterial suspensions, which inadvertently increase the moisture content of an already saturated peat matrix, potentially negating the benefits of the treatment. Moreover, there is a lack of research that bridges the gap between laboratory-scale testing and macro-scale structural performance through integrated numerical modeling.

To address these limitations, this study proposes a novel sequential bio-augmentation approach utilizing granulated bacterial formulations. This innovative strategy involves the synergistic application of granulated Pseudomonas putida for the initial decomposition of ligninolytic fiber compounds, followed by granulated Bacillus pasteurii to facilitate MICP-based binding. The use of encapsulated granules at a dosage of 6.75% is a key technical innovation designed to minimize additional free water while ensuring the long-term viability and controlled release of the bacterial consortium within the acidic peat environment. By breaking down the fibrous organic skeleton before inducing calcite precipitation, this sequential method aims to create a more compact and reinforced soil fabric.

Furthermore, this research integrates laboratory-derived engineering parameters into high-fidelity numerical simulations to evaluate the real-world performance of a pedestrian bridge foundation in Palangka Raya. By utilizing structural load data from SAP2000 and conducting two-dimensional finite element analysis in Plaxis 2D, this study quantifies the impact of bio-stabilization on the stability and serviceability (settlement) of shallow foundations. The primary objective is to demonstrate that granulated bio-augmentation can significantly reduce vertical settlement and foundation dimensions, providing an efficient, cost-effective, and environmentally friendly alternative to traditional geotechnical practices on problematic tropical peat deposits.

II. LITERATURE REVIEW

2.1 Peat Soil

Peat soil is a type of soil with an organic matter content of more than 75%, formed from incompletely decomposed plant remains under water-saturated conditions. This soil has unique characteristics that are very different from those of mineral soils such as clay, as its moisture content can reach 600% and it exhibits very high compressibility and low shear strength [6].

Indonesia has approximately 13,43 milion hectares of peatlands spread across three major islands: Sumatra, Kalimantan, and Papua [7]. Kalimantan is the region with the second-largest peatland area after Sumatra, with 4,5 million ha of peatland [7]. The Kalimantan region, particularly the city of Palangka Raya, is characterized by peat with high organic and water contents and low unit weight and shear strength parameters, resulting in very poor soil bearing capacity and high susceptibility to excessive deformation when subjected to loads [5].

2.2 Bioaugmentation

Bioaugmentation is a technique used to enchance the decomposition capacity of an environment by adding a suitable single-strain culture or bacterial consortium solution [8]. Bioaugmentation is an environmentally friendly and economically viable bioremediation approach because it utilizes microorganisms (bacteria) [9].

2.3 Microbially Induced Calcite Precipitation (MICP)

Microbially Induced Calcite Precipitation (MICP) is a soil improvement technique that uses microorganisms to alter and enhance the physical and mechanical properties of soil [10]. This soil stabilization process utilizes bacterial metabolism to naturally produce calcium carbonate, which then binds soil particles, improving cohesion, the angle of repose, and the mechanical strength of the soil [11].

2.4 Pseudomonas putida

Pseudomonas putida is a gram-negative, aerobic bacterium commonly found in water and soil; it has a slender rod-shaped structure and belongs to the genus Pseudomonas. This bacterium is known for its ability to produce ligninolytic enzymes that break down organic compounds into simpler compounds, thereby making peat fibers denser and more stable [12].

2.5 Bacillus pasteurii

Bacillus pasteurii is a gram-positive, aerobic bacterium that is predominantly used in MICP. Bacillus pasteurii produces the enzyme urease, which hydrolyzes urea into carbonate ions that then react with calcium ions to form calcium carbonate ($CaCO_3$) precipitates. These precipitates fill the pores and bind peat particles, thereby increasing soil strength [13].

2.6 Software SAP2000

SAP2000 is structural analysis and design software developed by Computers and Structures, Inc. (CSI). This software is widely used in the analysis of various types of civil structures, including buildings, bridges, towers, and other infrastructure. SAP2000 can perform linear and nonlinear analyses, both static and dynamic, and evaluate structural responses to various load combinations in accordance with applicable design standards [14].

In this study, SAP2000 was used to build a three-dimensional (3D) model of a Pedestrian Bridge to obtain joint reactions based on load combinations in accordance with SNI 1725:2016. The vertical reactions obtained from the analysis were then used as design loads in the evaluation of bearing capacity and the design of shallow foundations.

2.7 Soil Bearing Capacity According to Terzaghi

Several methods can be used to calculate soil bearing capacity, including the Terzaghi method [15]. The equation for calculating the bearing capacity of a square foundation is as follows:

$$q_u = 1{,}3cN_c + \gamma_s D_f N_q + 0{,}4\, B\gamma\, N_\gamma \qquad (1)$$

Where:

qu : ultimate bearing capacity (kN/m²)
c : cohesion (kN/m²)
γ_s : unit weight of soil (kN/m³)
γ' : effective unit weight of soil (kN/m³)
Df : foundation depth (m)
B : foundation width (m)
L : foundation length (m)
Nc, Nq, Nγ : Terzaghi bearing capacity factors

The allowable bearing capacity is calculated by dividing the ultimate bearing capacity by a specific safety factor. According to SNI 8460:2017, the minimum recommended safety factor for shallow foundations is 3. Furthermore, the allowable bearing capacity must be verified against the foundation settlement criteria. If the analysis results indicate that the settlement exceeds the tolerance limit, the bearing capacity must be recalculated iteratively until the settlement value meets the specified requirements.

2.8 Software PLAXIS 2D

PLAXIS 2D is a geotechnical analysis software based on the Finite Element Method (FEM) designed to simulate soil behavior and its interaction with structures. This software is widely used to analyze various geotechnical problems, such as soil deformation, settlement, slope stability, retaining walls, excavations, and soil–structure interaction, considering the nonlinear behavior of soil material [16].

In this study, PLAXIS 2D was used to model the interaction between shallow foundations and peat soil based on geotechnical parameters obtained from laboratory test results. Numerical simulations were performed to evaluate the stress distribution and magnitude of foundation settlement due to vertical loads obtained from structural analysis results using SAP2000.

III. METHODOLOGY

The overall research methodology adopted in this study is illustrated in **Fig. 1** The research consisted of soil sampling, biological stabilization, laboratory characterization, finite element modelling, and performance evaluation of shallow foundation on tropical peat.

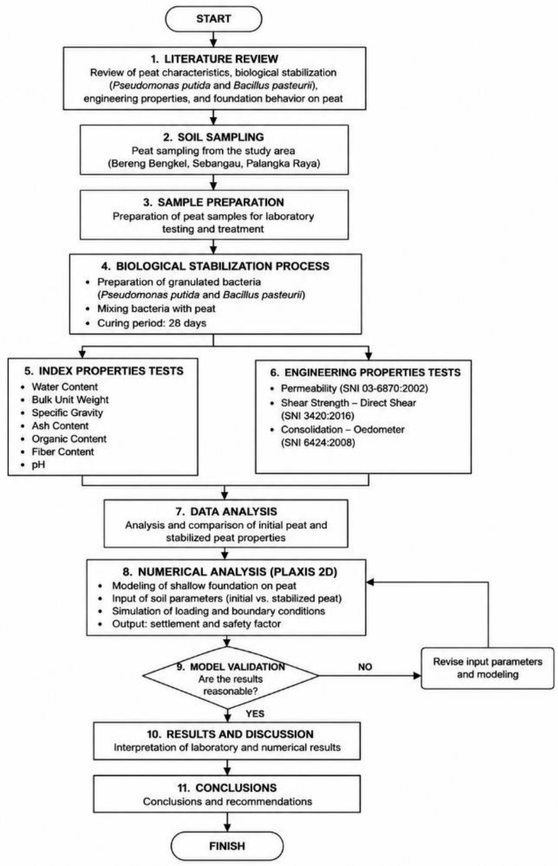


Fig. 1 Research Methodology Adopted in This Study

3.1 Site Characterization and Material Sampling

The peat soil samples were extracted from Bereng Bengkel, Palangka Raya, Central Kalimantan, Indonesia. This site was selected as it represents a typical tropical peat environment characterized by an extremely high water table, significant thickness, and a fibrous organic matrix that imposes severe geotechnical constraints. Initial characterization revealed that the peat possesses an organic content exceeding 99.7%, with natural water content reaching approximately 622%, which is characteristic of highly compressible organic deposits. The subsurface stratigraphic profile adopted for the numerical phase consists of a 3 m thick peat deposit, underlaid by a 7 m sand layer and a 5 m silty sand layer, providing a realistic geological context for the foundation performance evaluation.The location of the peat sampling site and the investigated bridge are presented in **Fig. 2**.

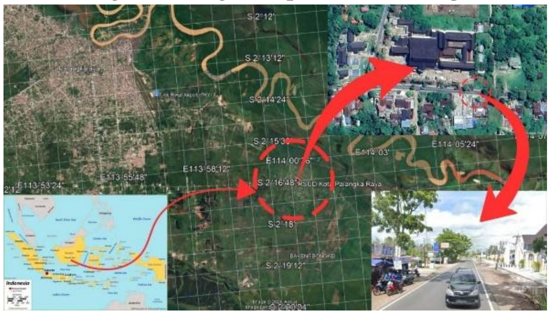


Fig. 2 Location of The Peat Sampling Site and The Investigated Pedestrian Bridge in Palangka Raya, Central Kalimantan, Indonesia

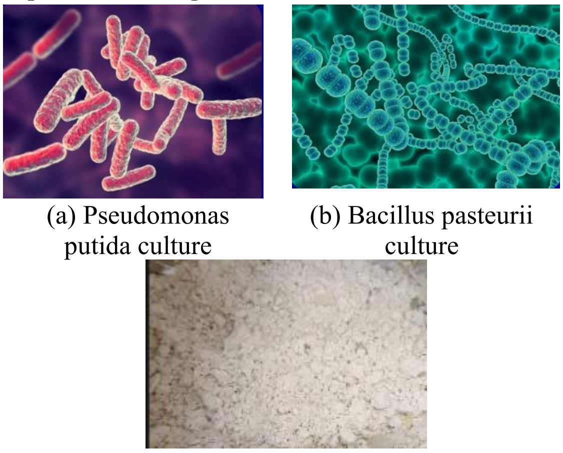
3.2 Sequential Bio-augmentation Strategy and Granular Formulation

To overcome the limitations of traditional liquid bio-stabilizers, this study employed a novel granular formulation of a synergistic bacterial consortium. The stabilization process followed a dual-mechanism sequential approach:

Phase I: Fiber Biodegradation. Pseudomonas putida was utilized for its ability to secrete ligninolytic enzymes [5]. This stage targets the breakdown of complex organic fibers into a denser, more stable matrix, effectively reducing the void ratio and improving the initial soil fabric.

Phase II: Microbially Induced Calcite Precipitation (MICP). Bacillus pasteurii, a highly ureolytic bacterium, was introduced to catalyze the hydrolysis of urea into carbonate ions [10], [11]. In the presence of a calcium source, this process induces the precipitation of calcium carbonate ($CaCO_3$) crystals, which act as a biological binder to bridge soil particles and enhance inter-particle friction.

Both bacterial species were formulated into encapsulated granules to minimize the addition of free water—a critical factor in maintaining the stability of peat—and applied at a dosage of 6.75% each based on the oven-dried mass of the peat. All treated specimens were cured in airtight containers for 28 days under controlled conditions (pH 3.3 to 6.2) to ensure optimal bacterial activity and structural development.The morphology of the bacterial cultures and the prepared granular product are presented in **Fig. 3**.



(a) Pseudomonas putida culture

(b) Bacillus pasteurii culture

(c) Granulated bacterial products

Fig. 3 Preparation of Biological Stabilizier: (a) Pseudomonas putida culture, (b) Bacillus pasteurii culture, and (c) Granulated bacterial products

The stabilization mixture consisted of 6,75% granulated Pseudomonas putida and 6,75% granulated Bacillus pasteurii, calculated based on the oven-dried mass of peat. Pseudomonas putida was incorporated to accelerate the biodegradation of peat fibers[5] and organic matter, thereby reducing the fibrous structure of the peat matrix. Subsequently, Bacillus pasteurii, a ureolytic bacterium, was introduced to promote calcium carbonate precipitation through the Microbially Induced Calcite Precipitation (MICP) mechanism. The combined application of both bacterial species was intended to improve the physical and mechanical properties of tropical peat while providing a more environmentally sustanable alternative to conventional chemical stabilization.

After through mixing, the stabilized peat specimens were sealed in airtight containers to minimize moisture loss and prevent contamination during curing. All specimens were cured for 28 days under controlled laboratory conditions before laboratory testing The engineering properties obtained from untreated and biologically stabilized peat were subsequently used as material parameters for finite element modelling in Plaxis 2D.

3.3 Laboratory Testing

A comprehensive suite of laboratory tests was executed to quantify the physical and mechanical transformations induced by the bio-treatment. The testing program was divided into two main categories: Physico-Chemical Characterization: This included the determination of water content, organic/ash content, bulk unit weight, specific gravity, pH, and fiber content. These parameters were critical for validating the degree of organic decomposition and mineral enrichment. Engineering Performance Testing: The mechanical behavior was evaluated through one-dimensional consolidation (compressibility), direct shear (strength parameters: c and ϕ), and constant-head permeability tests. These laboratory-derived parameters provided the necessary inputs for the subsequent constitutive modeling in the finite element analysis.

3.4 Shallow Foundation of Pedestrian Bridge

This study bridged the gap between material-scale results and structural-scale performance through an integrated numerical workflow involving SAP2000 and Plaxis 2D. Structural Analysis (SAP2000): A 3D model of a pedestrian bridge (9 m span, 2.5 m width) was analyzed according to SNI 1725:2016 [17] to derive the critical support reactions. A maximum vertical load of 255.29 kN was identified as the design basis for the foundation. Thethree-dimensional SAP2000 model of the pedestrian bridge, developed to represent the structural configuration, member geometry, and support conditions used in the analysis are illustrated in **Fig. 4**.

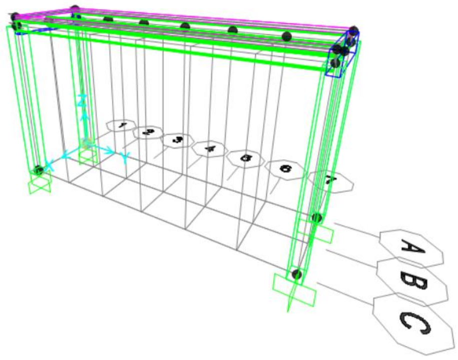


Fig. 4 Three-dimensional SAP2000 model of the pedestrian bridge

The critical loading condition produced a vertical load of 255.29 kN. The vertical load was subsequently used to determine the required shallow foundation dimensions by evaluating the allowable bearing capacity and settlement criteria according to the SNI 8460:2017 [18].

Geotechnical Simulation (Plaxis 2D): A two-dimensional plane strain finite element model was developed to evaluate the soil-foundation interaction. The Mohr-Coulomb constitutive model was selected to represent the elastoplastic behavior of the peat, utilizing the stiffness (Young's modulus) and shear strength parameters obtained from the 28-day stabilized samples.

Staged Construction Procedure: The numerical analysis followed a four-stage sequence: (1) generation of initial geostatic stresses, (2) activation of the foundation elements, (3) application of the 255.29 kN vertical load, and (4) a safety analysis using the phi-c reduction method to determine the global factor of safety.

3.5 Finite Element Modelling

The behaviour of the shallow foundation constructed on initial condition and biologically stabilized peat was evaluated using the finite element software Plaxis 2D. A two dimensional plane strain model was developed to simulate the soil foundation interaction under static loading conditions. The numerical analysis employed the Mohr-Coloumb constitutive model, which was selected because it provides an effective representation of elastoplastic soil behaviour while requiring engineering parameters commonly obtained from laboratory testing.

The subsurface profile was represented by a three layer soil system consisting of peat, sand, and silty sand. The uppermost layer comprised a 3m thick peat deposit, extending from the ground surfave to a depth of -3 m, representing the intial condition or biologically stabilized peat. Beneath the peat, -7 m thick sand layer extended from -3 m to -10 m, followed by a 5 m thick silty sand layer from -10 m to -15 m. This stratigraphic profile was entablished to represent the subsurface conditions adopted in the numerical analysis and to provide a realistic foundation for settlement evaluation.

The groundwater table was assumed to coincide with the ground surface, representing the saturated field conditions typically encountered in tropical peatlands. This assumption reflects the natural hydrogeological characteristic of peat deposits, where the groundwater level remains close to the surface throughout most of the year, thereby influencing the effective stress distribution, compressibility, and settlement behaviour of the foundation system. The finite element model included the geometry of the pedestrian bridge shallow foundation. Soil layers/stratigraphy and shallow foundation used in the numerical simulation are illustrated in **Fig. 5** and **Fig. 6**.

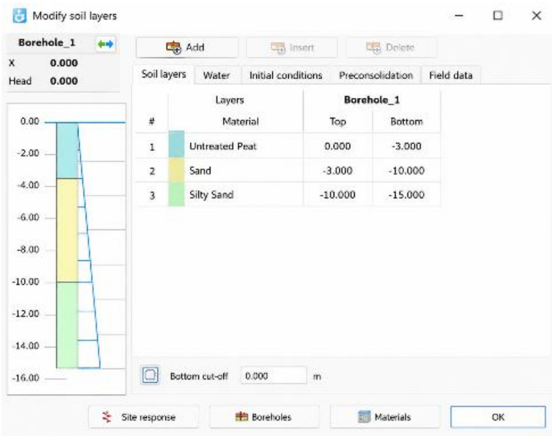


Fig. 5 Model Geometry Finite Element Modelling Plaxis 2D

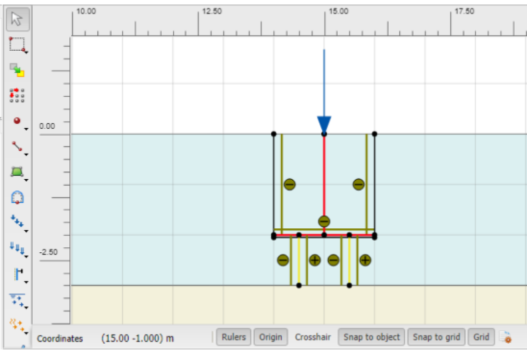


Fig. 6 The Geometry of The Pedestrian Bridge Shallow Foundation

3.6 Numerical Analysis Procedure

The numerical simulation was carried out using the staged construction procedure implemented in Plaxis 2D. The analysis consisted of four consecutive stages: (1) generation of the initial in-situ stress condition, (2) activation of the shallow foundation element, (3) application of incremental vertical loading, and (4) safety analysis using the phi-c reduction method. The loading sequence was designed to represent the service condition of the pedestrian bridge foundation. Both untreated and biologically stabilized peat models were analysed under identical loading conditions to ensure a consistent performance comparison. Phase of staged construction in the numerical simulation are illustrated in

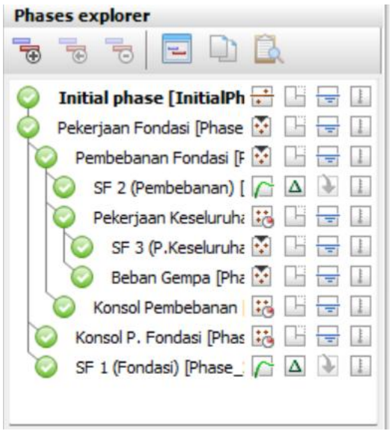


Fig. 7 Phase Of Staged Construction Numerical Simulation

3.7 Performance Indicators for Stability and Serviceability

The effectiveness of the granular bio-stabilization was benchmarked against two primary performance indicators: Serviceability and Stability. This dual-criteria approach ensures that the proposed biological method not only prevents shear failure but also maintains the functional integrity of the pedestrian bridge throughout its service life.

IV. RESULT AND DISCUSSION

4.1 Physico-Chemical Transformation and Microstructural Evolution

The index properties of initial condition and biologically stabilized peat were evaluated to investigate the influence of bacterial treatment on the physical characteristic of tropical peat. The laboratory result for index properties are summarized in **Table 1**.

Table 1 Index Properties of Initial Condition and Biologically Stabilized

No	Test	Unit	Initial Peat	Stabilized Peat (28 Days)
1.	Water Content (w)	%	622,108	175,693
2.	Bulk Unit Weight (γ)	g/cm³	1,164	0,517
3.	Specific Gravity (Gs)	-	1,657	1,572
4.	Ash Content	%	0,241	1,750
5.	Organic Content	%	99,759	98,250
6.	Fiber Content	%	50,034	20,067
7.	pH	-	3,387	6,200

As presented in **Table 1**, the dual-stage bio-augmentation significantly modified the physico-chemical properties of the tropical peat. After the 28-day curing period, the soil pH surged from an acidic 3.39 to a near-neutral 6.20. This alkalinization is a critical indicator of successful biological activity; the increase in pH not only reflects the urea hydrolysis catalyzed by B. pasteurii but also creates a more hospitable environment for sustained microbial metabolism in the otherwise hostile peat matrix. Furthermore, the ash content increased from 0.24% to 1.75%, while the organic content saw a corresponding decline. These shifts represent the relative enrichment of inorganic minerals within the soil fabric, primarily attributed to the bio-induced precipitation of calcium carbonate ($CaCO_3$).

A pivotal finding in this study is the 60% reduction in fiber content, which plummeted from 50.03% to 20.07%. This drastic transformation confirms the efficacy of P. putida in secreting ligninolytic enzymes that degrade the complex organic skeleton of the peat. By breaking down these fibrous strands, the bacteria facilitate the collapse of large macropores, leading to a more compact soil matrix. This is further evidenced by the substantial reduction in water content—from 622.1% to

175.7%—as the degradation of fibers releases bound water, which is subsequently expelled as the soil matrix densifies.

4.2 Enhancement of Geotechnical Engineering Properties

The engineering properties of the initial peat were determined to provide the fundamental parameters required for the numerical analysis. Laboratory testing included permeability, direct shear, and one dimensional consolidation tests in accordance with the applicable Indonesian National Standards (SNI).

No.	Test	Standard	Parameter (Symbol)	Value	Unit
1.	Permeability	SNI 03-6870, 2002	k	0.00001908	cm/s
2.	Shear Strength	SNI 3420, 2016	ϕ	6.407	°
			c	0.1731	kg/cm²
3.	Consolidation	SNI 6424, 2008	Δh	2.088	mm
			Cc	7.154	-
			Cv	0.0133	cm²/min

Table 2 Engineering Properties of Initial Condition and Biologically Stabilized

As presented in **Table 2**, The mechanical response of the stabilized peat showed a direct correlation with the observed physico-chemical changes. The biological treatment enhanced the internal friction angle (ϕ) and cohesion (c), fundamentally shifting the shear strength envelope of the material. This reinforcement is theorized to stem from the "bridging effect" of $CaCO_3$ crystals; as B. pasteurii induces MICP, the resulting calcite precipitates act as biological cement, binding the remaining organic particles and decomposed fibers at their contact points.

Furthermore, the stiffness of the peat, represented by the modulus of elasticity, was significantly improved. This increase in stiffness is vital for peatlands, where settlements are typically governed by high compressibility rather than shear failure alone. The reduction in the compression index (Cc) from 7.154 to lower levels indicates that the bio-stabilized peat is less susceptible to volume change under external loading. Consequently, the allowable bearing capacity (qall) surged by 273%, increasing from 65.40 kN/m² to 243.84 kN/m².

4.3 Numerical Simulation: Foundation Design and Optimization

A structural analysis of the pedestrian bridge was performed using SAP2000 software to determine the support reactions as the design load for the foundation. Based on the analysis results, the critical load combination produced a vertical load of 255.29 kN, which was subsequently used as the working load in the design of the shallow foundation.

A preliminary design was conducted for three soil conditions, initial (peat soil before stabilization), stabilization using bacterial granules for 28 days, and an ideal condition as a comparison based on previous research with the same curing period by Dewi Janti (2025) [19]. The foundation dimensions were determined based on compliance with the bearing capacity and settlement requirements. Based on the preliminary design, the planned dimensions for these three dimensions are shown in **Table 3**.

Table 3 Preliminary Shallow Foundation Dimensions under Different Peat Soil Conditions

Condition	Initial	Stabilization Bacterial Granules	Ideal
Dimensions (m)	2	1.1	1.5

The preliminary design results shown on **Table 3** that the initial condition requires foundation dimensions of 2 × 2 m, whereas after stabilization using bacterial granules for 28 days, the foundation dimensions can be reduced to 1.1 m × 1.1 m. For comparison, the ideal condition requires foundation dimensions of 1.5 × 1.5 m. These results show that stabilization using bacterial granules can reduce the foundation dimensions by 45% compared to the initial conditions and by 26.7% compared to the reference conditions.

The integration of laboratory parameters into Plaxis 2D numerical models provided a macro-scale validation of the stabilization efficacy. In the initial (untreated) state, a 2.0 × 2.0 m shallow foundation supplemented with 1.0 m mini piles was required to achieve a baseline safety factor of 2.634. This highlights the inherent inability of natural peat to support even lightweight structures without extensive and costly secondary reinforcement.

In contrast, the biologically stabilized peat model enabled a 45% reduction in foundation dimensions (to 1.1 × 1.1 m) while simultaneously eliminating the need for mini piles. Despite the smaller footprint and lack of auxiliary piles, the stabilized system achieved a superior global safety factor of 3.095. This optimization represents a significant advancement in geotechnical design, suggesting that sequential bioaugmentation can transform a problematic subgrade into a competent load-bearing stratum, thereby reducing material costs and construction complexity.

4.4 Bearing Capacity Evaluation

The bearing capacity evaluation was performed to quantify the improvement in peat soil performance after bacterial granule stabilization. The allowable bearing capacity was determined for the initial, stabilized, and reference conditions using the same design approach. The calculated allowable bearing capacities are summarized in **Table 4**.

Table 4 Comparison of Allowable Bearing Capacity under Different Peat Soil Conditions

Condition	Initial	Stabilization Bacterial Granules	Ideal
Allowable Bearing Capacity (kN/ m²)	65.40	243.84	379.25

Based on **Table 4**, peat soil stabilization using bacterial granules significantly increased the allowable bearing capacity—from 65.40 kN/m² under initial conditions to 243.84 kN/m² after the stabilization process. This increase had a direct impact on the required dimensions of shallow foundations, where the foundation size could be reduced from 2 × 2 m under initial conditions to 1.1 × 1.1 m after stabilization. These dimensions were more efficient than those under ideal conditions, which still required a size of 1.5 × 1.5 m. These results demonstrate that stabilization using bacterial granules not only enhances the soil's bearing capacity but also provides high efficiency in foundation design through reduced dimensions, thereby potentially reducing material requirements, construction costs, and project area. Therefore, the bacterial granule stabilization method can serve as an effective and economical alternative for improving the performance of peat soil as a subgrade for shallow foundations.

A critical distinction emerged when comparing the proposed bacterial-granule stabilization method with the reference biopolymer condition. Although the reference condition achieved the highest global safety factor (SF = 3.264), its vertical settlement reached 0.03992 m, which is very close to the allowable settlement limit of 0.04 m. This indicates a relatively small tolerance for additional loading or field variability.

The biologically stabilized peat investigated in this study produced the most reliable serviceability performance, with a vertical displacement of only 0.01440 m. This represents a 48.1% reduction in settlement compared to the initial condition. This finding is of paramount importance for Q1-level research: it demonstrates that while traditional stabilization often targets "strength" (Safety Factor), the proposed sequential bioaugmentation specifically enhances "stiffness" (settlement control). By providing a comfortable margin of safety in both stability and serviceability, this method offers a robust and balanced solution for infrastructure development on tropical peat

4.5 Numerical Simulation: Foundation Design and Optimization

The performance of the shallow foundation constructed on tropical peat was evaluated using the finite element method implemented in Plaxis 2D. The numerical analysis aimed to investigate the influence of biological stabilization on the settlement behaviour and overall stability of the foundation by comparing three soil conditions, namely Initial Peat, Biologically Stabilized Peat, and the Ideal Condition adopted from previous studies. All numerical models were analysed under identical foundation geometry, loading conditions, groundwater level, and boundary conditions to ensure that the observed differences were solely attributed to variations in the engineering properties of the peat. The engineering parameters adopted in the finite element analysis are presented in **Table 5**.

Table 5 Material Parameters Used in the PLAXIS 2D Numerical Model

Soil Parameter	Symbol	Peat (Initial Condition)	Peat Stabilized (28 DAYS)	Sand	Silty Sand	Ideal Condition (from Previous Studies)	Unit
Material Model	-	*Mohr-Coulomb*	*Mohr-Coulomb*	*Mohr-Coulomb*	*Mohr-Coulomb*	*Mohr-Coulomb*	-
Drainage Type	-	*Undrained B*	*Undrained B*	*Drained*	*Drained*	*Undrained B*	-
Unsaturated Unit Weight	γunsat	11.413	5.07	11.67	17.46	11.40	kN/m³
Saturated Unit Weight	γsat	10.64	10.68	13.44	21.50	12.30	kN/m³
Poisson's Ratio	ν	0.470	0.421	0.330	0.316	0.36	-
Cohesion	c	16.975	44.83	8.83	5.88	17.30	kN/m²
Friction Angle	φ'	6.407	15.91	30.51	32.58	24.80	°
Dilatancy Angle	ψ	0.00	0.00	0.00	0.00	0.00	°
Initial Void Ratio	e0	9.28	7.36	1.01	0.78	4.40	-
Interface Strength Ratio	R	1.00	1.00	1.00	1.00	1.00	-
Young's Modulus	E0	500	2125.20	30000	15000	1250.0	kPa
Kx	*Kx*	0.0164810	0.008241	6.2467	0.01728	0.23328000	m/day
Ky	*Ky*	0.0164810	0.008241	6.2467	0.01728	0.23328000	m/day

The Initial Peat parameters were obtained from laboratory characterization, while the Biologically Stabilized Peat parameters represent the proposed stabilization scenario after 28 days of curing using 6.75% granulated Pseudomonas putida and 6.75% granulated Bacillus pasteurii based on the oven-dried peat mass. An additional Ideal Condition was incorporated as a reference model using engineering parameters reported in previous studies to represent the optimum performance of improved peat. The underlying Sand and Silty Sand layers remained unchanged in all numerical models.

To evaluate the effectiveness of biological stabilization in improving foundation performance and optimizing foundation dimensions, different foundation configurations were adopted for each model according to the engineering characteristics of the supporting soil. The initial peat model employed a 2.0 × 2.0 m shallow foundation combined with 1.0 m mini piles to compensate for the very low bearing capacity of the untreated peat. In contrast, the biologically stabilized peat model utilized only a 1.1 × 1.1 m shallow foundation, indicating that the improvement in soil engineering properties after stabilization enabled the elimination of the mini piles while maintaining structural stability. As a benchmark, the ideal condition adopted from previous studies was modelled using a 1.2 × 1.2 m shallow foundation without additional ground reinforcement. The comparison of vertical settlement contours and global factor of safety obtained from the finite element analysis is presented in **Fig. 8**, **Fig. 9**, and **Fig. 10**.

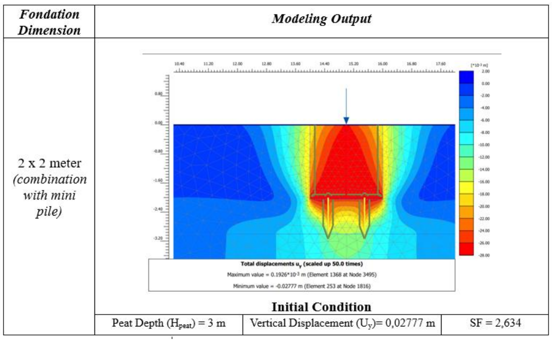


Fig. 8 Vertical Settlement Contours of The Initial Peat

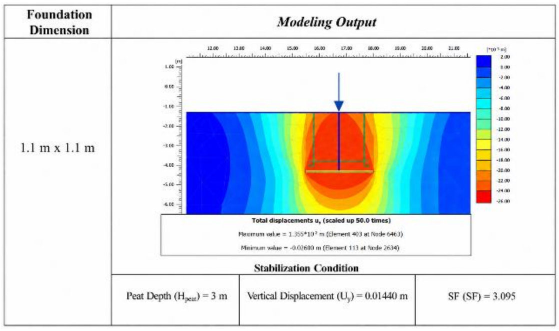


Fig. 9 Vertical Settlement Contours of The Biologically Stabilized Peat

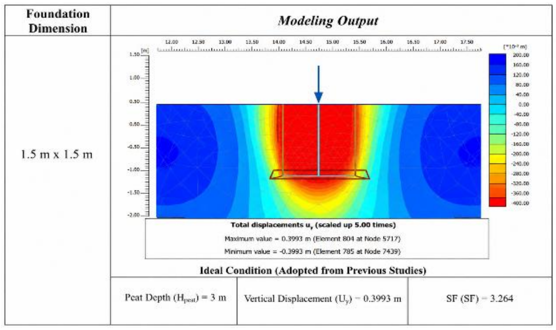


Fig. 10 Vertical Settlement Contours of The Ideal Condition

The numerical analysis revealed distinct foundation responses under the three investigated soil conditions, as summarized in Table 6. The initial peat condition exhibited a vertical displacement of 0.02777 m with a global safety factor of 2.634, despite employing a larger 2.0 × 2.0 m shallow foundation combined with 1.0 m mini piles. These results indicate that the low stiffness and weak shear strength of untreated peat significantly affected the bearing performance of the foundation system.

Following biological stabilization using Pseudomonas putida and Bacillus pasteurii, the foundation performance improved considerably. The stabilized peat model produced the smallest vertical displacement of 0.01440 m while maintaining a satisfactory safety factor of 3.095, even though the foundation dimensions were reduced to 1.1 × 1.1 m and the mini piles were completely eliminated. This improvement demonstrates that biological treatment effectively enhanced the engineering properties of peat, allowing a more efficient shallow foundation design without compromising structural stability.

The ideal condition adopted from previous studies yielded the highest global safety factor (SF = 3.264) with a vertical displacement of 0.03992 m using a 1.5 × 1.5 m shallow foundation. Although this model provided the greatest overall stability against failure, its predicted settlement was higher than that of the biologically stabilized peat investigated in the present study. This finding indicates that the previous study emphasized maximizing bearing capacity and global stability, whereas the proposed biological stabilization method was more effective in reducing settlement under the applied loading conditions.

Table 6 presents the comparative evaluation of the PLAXIS 2D modeling results in terms of vertical displacement and global safety factor for the initial peat, biologically stabilized peat, and the ideal condition adopted from previous studies.

Table 6 Comparative Evaluation Of Settlement And Safety Factor

No	Condition	Vertical Displacement (Uy)	Safety Factor (SF)
1.	Initial Peat	0,02777 m	2,634
2.	Biologically Stabilized Peat	0,01440 m	3.095
3.	Ideal Condition	0,03992 m	3,264

Overall, the numerical results demonstrate that biological stabilization substantially enhanced the performance of tropical peat as a foundation subsoil. Compared with the untreated condition, the proposed stabilization method reduced the predicted settlement by approximately 48.1% while increasing the safety factor from 2.634 to 3.095. Furthermore, these improvements enabled the shallow foundation dimensions to be reduced from 2.0 × 2.0 m (with mini piles) to 1.1 × 1.1 m without additional deep foundation elements. Although the ideal condition from previous studies achieved a slightly higher safety factor (3.264), the biologically stabilized peat produced the lowest settlement among all investigated cases. Therefore, the proposed biological stabilization method offers a practical and economical alternative for supporting shallow foundations on tropical peat by simultaneously improving soil performance and optimizing foundation dimensions.

4.4 Discussion

The numerical analysis of the three modeling scenarios provides clear evidence of how the mechanical behavior of tropical peat governs the serviceability and stability of a shallow foundation system. Referring to the allowable vertical settlement criterion adopted in this study, 0.04 m (40 mm), the initial (untreated) peat condition produced a vertical displacement (Uy) of 0.02777 m, which lies within the permissible limit, and a global safety factor of 2.634. This result was only achieved, however, by employing a larger foundation footprint together with supplementary mini piles, underlining the inherently poor engineering characteristics of natural peat — its high compressibility, low shear strength, and large initial void ratio — which require substantial structural reinforcement simply to keep settlement within an acceptable range.

Following biological stabilization using Pseudomonas putida and Bacillus pasteurii, the model showed a marked improvement in performance. The vertical displacement decreased to 0.01440 m — the smallest settlement recorded among all three scenarios and well within the 40 mm allowable limit — while the safety factor increased to 3.095. This improvement was achieved with a substantially smaller foundation, reduced from 2.0 × 2.0 m to 1.1 × 1.1 m, and without relying on mini piles at all. The result indicates that microbially induced stabilization did not merely add strength at the margins; it fundamentally altered the peat's stiffness and shear behavior (reflected in the increase of cohesion, friction angle, and Young's modulus, and the reduction of the void ratio in the material parameters), enabling the soil to mobilize adequate bearing capacity on its own while comfortably satisfying the serviceability requirement.

The ideal condition, adapted from previous research findings, produced the highest safety factor of the three cases at 3.264, confirming its status as the upper bound of shear-strength performance among the scenarios considered. When evaluated against the 40 mm allowable settlement criterion, this scenario also satisfies the requirement, recording a vertical displacement of 0.03992 m — only 0.08 mm (about 0.2%) below the permissible limit. Although this scenario technically meets both the stability and serviceability criteria, the very narrow margin against the allowable settlement indicates that its serviceability performance is only marginally acceptable, leaving little room for variation in loading, material properties, or construction tolerances before the limit would be exceeded. This finding is instructive: it shows that a high safety factor against shear failure does not necessarily correspond to a comfortable margin in settlement performance, since the safety factor is governed primarily by the strength parameters (cohesion and friction angle), whereas settlement is governed by stiffness (Young's modulus) and the resulting stress-strain response.

Taken together, these results reveal an important distinction between stability and serviceability performance. Although all three scenarios ultimately satisfy both the safety factor requirement and the 40 mm allowable settlement limit, the biologically stabilized scenario provides the most balanced and reliable performance, combining the smallest settlement (0.01440 m, well within the allowable limit with a comfortable margin) with a substantially improved safety factor (3.095), achieved using a foundation nearly half the size of the untreated case and without any auxiliary piling system. In contrast, the ideal condition, despite achieving the highest safety factor, meets the settlement criterion only marginally, while the untreated peat requires additional structural reinforcement (a larger foundation and mini piles) to remain within acceptable limits at all. This demonstrates that biological stabilization offers the most efficient and robust improvement to tropical peat, enhancing both shear strength and stiffness in a way that yields a genuinely comfortable margin of safety in both stability and serviceability terms.

V. CONCLUSION

This study establishes a pioneering framework for the sustainable stabilization of tropical peatlands through a novel sequential bio-augmentation approach using granulated bacterial consortiums. By integrating multi-stage biological mechanisms with advanced numerical simulations, the research demonstrates a significant leap in the engineering performance of problematic organic soils. The following key conclusions are drawn:

First, the implementation of a dual-species sequential mechanism—utilizing Pseudomonas putida for targeted fiber biodegradation followed by Bacillus pasteurii for Microbially Induced Calcite Precipitation (MICP)—fundamentally transformed the peat fabric. The research confirms that P. putida successfully reduced fiber content by 60% (from 50.03% to 20.07%), effectively breaking down the ligninolytic organic skeleton and creating a denser soil matrix. This structural modification provided an optimal environment for B. pasteurii-induced MICP, which significantly enhanced inter-particle bonding and increased the soil pH from a highly acidic 3.39 to a near-neutral 6.20.

Second, the use of encapsulated granules at a 6.75% dosage proved to be a superior delivery system for tropical peat stabilization. Unlike traditional liquid bacterial suspensions that exacerbate the already excessive moisture content of peat, the granular formulation minimized additional water while ensuring bacterial viability during the 28-day curing period. This practical innovation resulted in a 273% increase in allowable bearing capacity, rising from 65.40 kN/m² to 243.84 kN/m², thereby validating the efficacy of granular bio-stabilization as a robust ground improvement strategy.

Third, the integration of laboratory parameters into Plaxis 2D finite element modeling provided critical insights into foundation optimization. The results demonstrate that biological stabilization enables a 45% reduction in shallow foundation dimensions (from 2.0 m to 1.1 m) and the total elimination of auxiliary mini-piles. Despite the reduced foundation footprint and lack of deep reinforcement, the stabilized peat achieved a superior global safety factor of 3.095, exceeding the minimum requirements set by SNI 8460:2017.

Fourth, this research highlights a critical distinction between geotechnical stability and serviceability performance. While benchmark "ideal conditions" may offer higher shear-strength safety factors, the proposed sequential bio-augmentation method achieved the most reliable settlement control, reducing vertical displacement by 48.1% (to 0.01440 m). By maintaining a comfortable margin (over 60%) below the 40 mm allowable settlement limit, this method ensures superior serviceability for lightweight infrastructure compared to traditional or alternative stabilization benchmarks that operate at the edge of permissible limits.

In summary, this study provides a sustainable, "green," and economically viable alternative to cement-based stabilization for tropical peat. The successful synergy between fiber degradation and mineral precipitation offers a robust solution for infrastructure development on organic soils. Future research is recommended to incorporate Total Plate Count (TPC) analysis to track long-term bacterial viability and to evaluate the California Bearing Ratio (CBR) of stabilized peat to further assess its feasibility for broader pavement and transport infrastructure applications.

VI. RECOMMENDATION

Considering that the biologically stabilized peat satisfied both the stability and serviceability requirements, whereas the ideal condition benchmark met the strength criterion but exceeded the allowable settlement limit, several recommendations are proposed for future development of this research and its practical application:

1. Total Plate Count (TPC) testing should be conducted on the granular bacteria before and/or during the stabilization process to verify the viability and quantity of surviving bacterial cells, thereby ensuring the effectiveness of the biological treatment.
2. The dry weight of the soil should be adopted as the basis for calculating the mixing percentage of the stabilizing agent, so as to produce a more accurate and consistent mixture proportion.
3. California Bearing Ratio (CBR) testing should be carried out on the stabilized peat to further evaluate the soil's bearing capacity, particularly with regard to assessing the feasibility and effectiveness of the stabilization results.

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