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Numerical Analysis of the Influence of Bamboo Chips Variations on Road Embankment Stability and Settlement

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Abstract

Soft soil is characterized by low bearing capacity, high compressibility, and substantial settlement, thereby frequently causing complications in road embankment construction. One viable method for soil improvement is stabilization utilizing eco-friendly materials, such as bamboo chips. However, research concerning the effects of varying bamboo chip mixtures on the stability and settlement of embankments constructed on soft soil remains limited. This study aims to analyze the impact of bamboo chip mixture variations on consolidation characteristics, embankment stability, and soft soil settlement, utilizing the finite element method via numerical analysis software. The investigation was conducted through one-dimensional consolidation testing (oedometer tests) on native soil and bamboo chip mixture variations of 25%, 30%, and 35%. The experimental results served as input parameters for the numerical modeling software to evaluate the safety factor and embankment settlement. The findings indicate that the incorporation of bamboo chips effectively enhances embankment stability and mitigates soil settlement compared to untreated soil conditions. The TA + BC (Native Soil + Bamboo Chips) 30% variation yielded the most optimal outcomes, exhibiting the lowest compression index and consolidation settlement, alongside a higher safety factor relative to the other variations. Overall, bamboo chips demonstrate significant potential as an economical and environmentally sustainable alternative stabilization material for road embankment construction over soft soils.

Keywords: Bamboo chips; consolidation; embankment stability; numerical analysis software; soft soil

1. Introduction

The construction of road embankments on soft soil remains a major challenge in geotechnical engineering, particularly in areas with saturated clay layers characterized by low bearing capacity, high compressibility, and low shear strength [1]–[3]. These conditions render embankments highly susceptible to settlement, lateral deformation, and potential slope failure if adequate soil improvement is not implemented [4], [5]. The reservoir (bozem) area of UPN "Veteran" Jawa Timur in East Surabaya is a prime example of such conditions, exhibiting surface Standard Penetration Test (N-SPT) values of less than 1 [3], a Liquid Limit (LL) of 69%, and a groundwater table at a depth of less than 1 m below the surface [6]. If road embankment construction is undertaken without appropriate soil improvement, the risks of excessive settlement and structural instability increase significantly [1], [3].

Various soil stabilization methods have been developed to enhance the mechanical characteristics of soft soils, ranging from chemical agents such as cement and lime to more eco-friendly natural materials [7], [8]. Bamboo-based materials are increasingly being researched as an alternative for soft soil reinforcement; the use of bamboo piles has been proven to improve embankment stability on coastal soft soils [9], [10]. One promising form of bamboo material for development is bamboo chips – fibrous bamboo flakes mixed directly into soft soil to enhance interparticle interaction and improve the mechanical behavior of the soil [11], [12]. The selection of bamboo chips is based on their abundant availability, low cost, and natural biodegradability, making them a sustainable alternative to synthetic reinforcement materials [7], [8].

The advancement of the finite element method through PLAXIS 2D software facilitates a comprehensive evaluation of embankment behavior on soft soil, including deformation patterns, stress distribution, and factor of safety [13], [14]. The Mohr-Coulomb model with an Undrained B approach is commonly utilized in preliminary geotechnical analyses due to its simple and representative parameters for saturated soft clay [15], [16]. Nevertheless, studies on bamboo chips as a soft soil

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mixture evaluated numerically remain highly limited compared to research on bamboo piles and woven bamboo mats [9], [10]. This study aims to analyze the effect of varying bamboo chip mixtures (0%, 25%, 30%, 35%) on the safety factor and road embankment settlement using PLAXIS 2D finite element software. Furthermore, it is expected to contribute as a reference for the design of road embankment construction in soft soil regions, a topic that has not yet been extensively evaluated through numerical analysis [13], [14], [17].

2. Literature Review

2.1. Road embankments and their problems

Road embankments built on soft soil face major challenges in the form of slope instability, low bearing capacity, and excessive settlement. Soft soil is characterized by high compressibility, low shear strength, and high water content approaching or exceeding the liquid limit, making it highly susceptible to failure and long-term deformation [18]. The frequency of embankment construction on soft soil continues to rise due to the limited availability of land suitable for infrastructure development [19].

2.2. Bamboo as a soil reinforcement material

Bamboo has long been recognized as a Bamboo is a natural material that possesses high tensile strength, offering significant potential as a sustainable geotechnical reinforcement. Studies demonstrate that the addition of bamboo fibers significantly increases the unconfined compressive strength (UCS) by up to 75% and soil cohesion by up to 195% compared to unreinforced soil, with an optimal fiber content of 0.75% and a fiber length of 10 mm [11]. Furthermore, bamboo fibers have been proven to enhance the shear strength of soil by increasing the internal friction angle and apparent cohesion, with the optimal fiber content remaining at approximately 0.75% [19].

2.3. Bamboo chips as a soil mixture

Bamboo chips possess distinct water absorption properties and function three-dimensionally within the soil matrix. Research by Shigematsu et al. indicates that the addition of bamboo chips and flakes provides a significant improvement effect on soft soil with high water content, and this effect is influenced by the differing water absorption properties of the chips and flakes [20]. Moreover, variations in the bamboo chip content directly affect the strength parameters and deformation characteristics of the soil-bamboo mixture [20]. Bamboo reinforcement in the form of grids, geotextiles, and geocells has also proven effective in increasing bearing capacity, reducing settlement, and controlling lateral displacement in soft soils [21].

2.4. Embankment slope stability

Embankment slope stability is analyzed based on the Factor of Safety (FS) value, where a slope is considered safe if FS $\geq$ 1.5. Numerical research using the Finite Element Method (FEM) shows that the incorporation of natural fibers, such as bamboo and wheat straw, into silty clay significantly improves shear strength and three-dimensional slope stability [22]. Slope analysis with PLAXIS 2D utilizing the Mohr-Coulomb model consistently demonstrates that natural material reinforcement can measurably increase the FS compared to unreinforced conditions [23].

2.5. Numerical analysis using FEM

Numerical analysis using FEM (PLAXIS) on embankments reinforced with a Bamboo-Geotextile Composite (BGC) reveals that the resulting deformation is lower than that of unreinforced embankments, with the FEM results being well-validated against field data [24]. Bamboo acting as a geogrid has also proven effective in reducing soil settlement, making it a highly promising and sustainable geotechnical solution [25].

2.6. Finite element method (FEM)

The Finite Element Method (FEM) has become the modern standard for analyzing complex geotechnical structures. The application of PLAXIS software with the Mohr-Coulomb constitutive model allows for a comprehensive simulation of stress, strain, and deformation distributions in embankments constructed over soft soil. Parametric analysis using FEM demonstrates that utilizing reinforcement columns in soft soil embankments can significantly reduce total foundation deformation, yielding results that are validated by field data [26]. Furthermore, the numerical modeling of bamboo-geotextile reinforced embankments using PLAXIS 2D has successfully verified settlement predictions against actual field monitoring data [24].

2.7. Embankments reinforcement

Embankment reinforcement using bamboo piles (*cerucuk*) in soft soil has been thoroughly investigated through both analytical approaches and numerical simulations. The simulation results indicate that variations in the spacing and configuration of the bamboo piles exert a significant influence on the bearing capacity and the critical height of the embankment [27]. Combining bamboo with geotextiles as a composite system has proven to be far more effective in increasing the FS and suppressing settlement compared to relying on geotextiles alone.

3. Research Methodology

3.1. Location and time of research

The research was conducted in the reservoir (bozem) area of UPN "Veteran" Jawa Timur, East Surabaya, East Java. This location exhibits typical soft soil characteristics with a shallow groundwater table of less than 1 m below the surface [1]. Soil samples were extracted at a depth of 1–2 m utilizing a hand auger and a Shelby tube, intentionally bypassing the backfill soil layer located at a depth of 0–1 m. Soil investigation data for the 3–30 m layer were acquired from the Faculty of Economics and Business (FEB) building project at UPN "Veteran" Jawa Timur, comprising bore logs and laboratory test results

[4]. The research program encompassed three primary stages: (1) laboratory consolidation testing; (2) determination of input parameters; and (3) numerical software modeling.

3.2. Research materials

3.2.1. Soft soil

The subgrade consists of sandy clayey silt with an N-SPT value of less than 1 [2], a Liquid Limit (LL) of 69%, a 100% degree of saturation, and a void ratio ranging from 1.257 to 2.834 within the 3–30 m layer [1], [5]. These characteristics render the research location highly representative as a case study for soft soil stabilization beneath road embankment construction.

3.2.2. Bamboo chips

The bamboo chips were prepared via sieving through 25 mm, 15 mm, and 5 mm meshes, yielding a weight composition of 20%:40%:40% for large, medium, and small sizes, respectively. Four mixture variations were utilized: 0%, 25%, 30%, and 35% relative to the dry weight of the soil [7], [11]. The mixture variations are detailed in Table 1.

Table 1. Bamboo chip mixture variations

Variations	Percentage of Bamboo Chips
Original Soil	0%
Variation 1	25%
Variation 2	30%
Variation 3	35%

3.3. Laboratory testing

The native soil samples were maintained in an undisturbed condition, whereas the mixture variations were treated as disturbed samples through oven drying, crushing, passing through a No. 16 sieve, homogeneous mixing, and a 1-day curing period [1]. Consolidation testing was conducted in accordance with ASTM D2435 [6] to determine the compression index (Cc), coefficient of consolidation (Cv), coefficient of permeability (k), initial void ratio (e_0), and consolidation settlement (Sc). The values of Cc and Cv were calculated using Equations (1) and (2) [1], [4]:

$$C_c = \frac{e_b - e_a}{\log(\frac{p_b}{p_a})} \quad (1)$$

where,
C_c : compression index
e_a : initial void ratio before loading
e_b : void ratio after loading
p_a : initial effective stress (kN/m^2)
p_b : final effective stress (kN/m^2)

$$C_v = \frac{0.848 \times {H_r}^2}{t_{90}} \quad (2)$$

where,
C_v : coefficient of consolidation (m^2/s)
H_r : maximum drainage path length (m)
t_{90} : time required to achieve 90% consolidation (s)

3.4. Finite Element Method numerical modeling

The modeling utilized a plane strain approach with the Mohr-Coulomb Undrained B constitutive model (Cu, φ = 0°) for the soft soil and a drained condition for the embankment [13]. The soil replacement layer was modeled at a depth of 0–3 m. A 5 m high embankment was constructed in two stages (2.5 m each) in accordance with the Bina Marga 2018 Specification Revision 2 [11]. A total surface load of 17.66 kN/m² (AC-WC + AC-BC pavement = 2.66 kN/m²; traffic load = 15 kN/m²) was applied based on the KIMPRASWIL Guidelines Pt T-10-2002-B [28]. The input parameters are presented in Table 2.

Table 2. Software material input parameters

Variation	γunsat (kN/m³)	γsat (kN/m³)	e_0	E_{50} (kN/m²)	Cu (kN/m²)	φ (°)	kx, ky (m/day)
Original Soil	11.78	19.19	1.68	429.83	14.76	0	6.60×10^{-5}
OS + BC 25%	12.08	13.81	0.90	1835.75	122.24	0	9.82×10^{-6}
OS + BC 30%	12.17	13.20	0.70	2449.05	158.60	0	8.03×10^{-6}
OS + BC 35%	11.77	12.91	0.71	1325.13	81.39	0	5.58×10^{-6}

Boundary conditions were set with horizontal fixity on the left and right sides of the model, and full fixity at the base. A medium-type mesh was utilized [13]. The analysis phases were as follows: (1) initial phase; (2) embankment stage 1 — plastic; (3) consolidation stage 1 — consolidation; (4) safety factor (SF); (5) embankment stage 2; (6) consolidation stage 2; (7) SF; (8) application of 17.66 kN/m² load; (9) final SF. The SF values were obtained via the phi-c reduction method [13].

4. Results and Discussion

The results of the consolidation tests on the native soil and the bamboo chip mixture variations are presented in Table 3.

Table 3. Soil consolidation parameters

Variation	e_0	Cv (m²/kN)	Cc	Cs	k (m/day)	Sc (mm)
Original Soil	1.68	6.19×10^{-6}	0.40147	0.0537	6.60×10^{-5}	0.899
OS + BC 25%	0.90	8.51×10^{-6}	0.21875	0.01067	9.82×10^{-6}	0.656
OS + BC 30%	0.70	8.71×10^{-6}	0.10588	0.02323	8.03×10^{-6}	0.355
OS + BC 35%	0.71	2.31×10^{-6}	0.28347	0.03294	5.58×10^{-6}	0.497

The incorporation of bamboo chips significantly influenced the reduction of the compression index (Cc) and initial void ratio (e0). The Cc value decreased from 0.401 (native soil) to 0.106 (TA + BC 30%), representing a 73.6% reduction in compressibility. The decrease in e0 from 1.68 to 0.70 indicates that the bamboo fibers occupy the inter-particle voids, thereby enhancing the density of the soil structure [17]. The lowest consolidation settlement (Sc) was observed in the TA + BC 30% variation (0.355 mm), a reduction of 60.4% compared to the native soil.

In the TA + BC 35% variation, the Cc (0.283) and Sc (0.497 mm) values exhibited an upward trend compared to the TA + BC 30% variation. This indicates the existence of an optimum fiber content within the mixture; excessive addition leads to a non-homogeneous distribution, creating inter-fiber voids that reduce stabilization effectiveness [15], [17]. This is consistent with findings from other natural fiber research, which demonstrates an optimal strength pattern within a specific range [15]. A comparison of Cc and Sc for all variations is illustrated in Fig. 1 and Fig. 2.

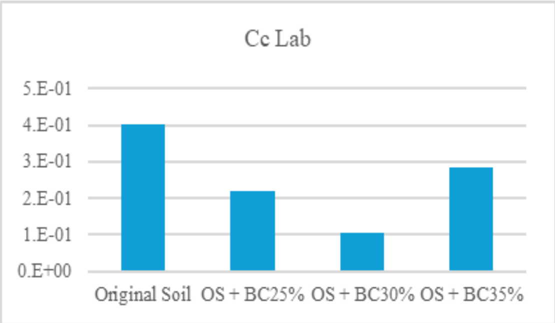

Figure 1. Graph of compression index (Cc)

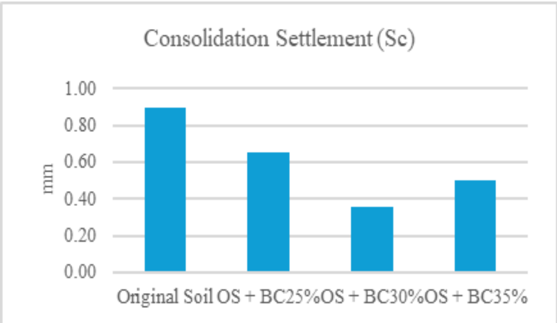

Figure 2. Graph of consolidation settlement (Sc)

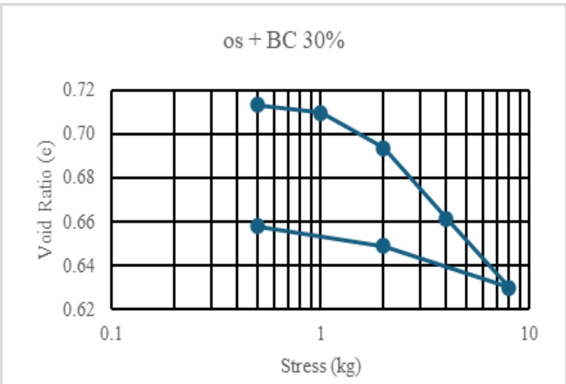

Figure 3. e-log p curve for the TA + BC 30% variations

4.1. Embankment stability analysis

The recapitulation of safety factor (SF) values for all variations and stages is shown in Table 4 (red cell = SF < 1.5; yellow cell = highest SF per stage).

Table 4. SF Results

Variation	SF Emb. 1	SF Cons. 1	SF Emb. 2	SF Cons. 2	SF Load	Status (SF>1.5)
Original Soil	1.850	1.850	1.403	1.403	1.490	Unsafe
OS + BC 25%	2.076	2.077	1.721	1.717	1.578	Safe
OS + BC 30%	2.085	2.076	1.723	1.717	1.585	Safe
OS + BC 35%	2.080	2.074	1.720	1.722	1.580	Safe

In the original soil, the SF values for the second embankment stage (1.403) and the loading stage (1.490) are below the minimum limit of SF = 1.5 [29], indicating that the unreinforced subgrade is unable to safely support the 5 m embankment. After the addition of bamboo chips, all variations produced an SF > 1.5 at all stages. The highest SF values at embankment stages 1 and 2 were obtained in OS + BC 30% (2.085 and 1.723), while at the final loading stage, the highest SF value was in OS + BC 30% (1.585).

The increase in SF occurs because the bamboo fibers distributed within the mixture form an interlocking mechanism between soil particles, thereby increasing the shear resistance against lateral deformation [11], [15]. This pattern is confirmed by changes in total displacement in the software: the slip surface in the original soil develops into the soft layer beneath the embankment (deep-seated failure), whereas in OS + BC 30%, the slip surface is shallower and lateral deformation is significantly reduced (Fig. 4). The comparison of SF for all variations is shown in Fig. 5.

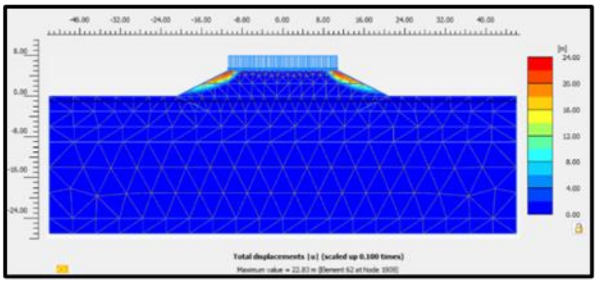

Figure 4. Total displacement of OS + BC 30%

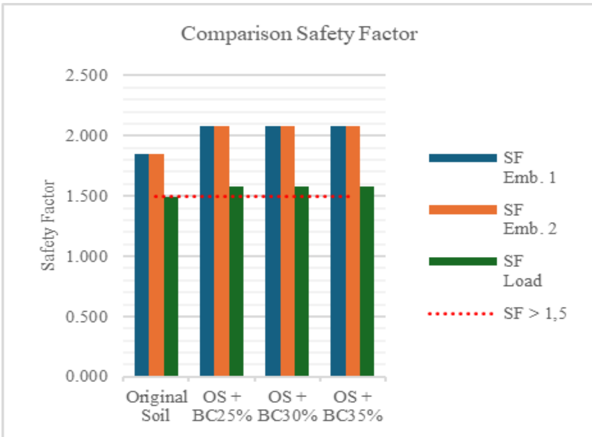

Figure 5. Comparison of safety factors at each loading stage

Table 5. Settlement Results

Variation	S1 (mm)	Rate 1 (mm/yr)	S2 (mm)	Rate 2 (mm/yr)	S3 (mm)	Rate 3 (mm/yr)	Rate 3 Reduction
Original Soil	262.2	14.57	486.0	14.46	587.3	9.55	—
OS + BC 25%	162.9	6.13	337.6	6.91	419.1	4.91	48.6%
OS + BC 30%	190.6	6.58	394.3	7.45	488.5	5.59	41.5%
OS + BC 35%	175.5	5.76	361.3	6.42	444.3	4.84	49.3%
Allowable Limit	—	< 20	—	< 20	—	< 20	—

4.2. Embankment settlement analysis

The recapitulation of settlement for all variations is shown in Table 5 (yellow cell = lowest rate; allowable limit row = 20 mm/year per KIMPRASWIL Guidelines [28]).

All variations meet the allowable settlement rate limit of < 20 mm/year [31]. The addition of bamboo chips reduced the settlement rate of the loading stage from 9.55 mm/year (original soil) to 4.84–5.59 mm/year (equivalent to a reduction of 41.5–49.3%). This reduction occurs because E_{50} increases from 655.80 kN/m² (original soil) to 1,259–2,153 kN/m² (mixture variations), ensuring the stress due to the load is distributed more evenly [11]. The OS + BC 35% variation produced the lowest rate across all stages (Fig. 6).

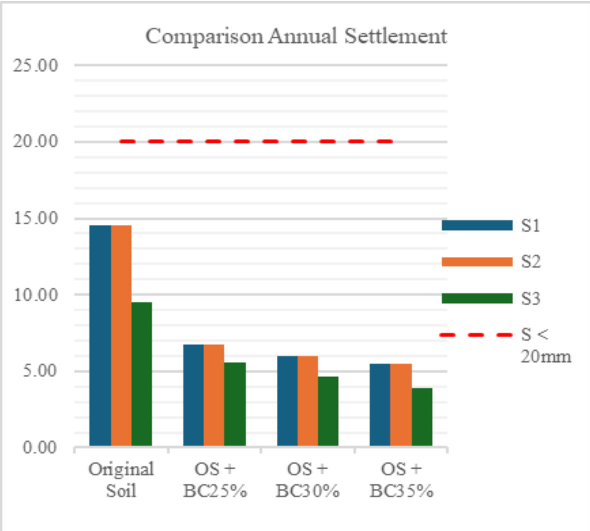

Figure 6. Comparison of annual soil settlement for each bamboo chip variation

4.3. Optimum variation

The OS + BC 35% variation is superior in the loading stage SF (1.585) and settlement rate (4.84 mm/year), while OS + BC 30% is superior in laboratory compressibility parameters (smallest Cc = 0.106; smallest Sc = 0.356 mm). The SF difference between the two at the loading stage is only 0.001, making them practically equivalent. Considering the consistency of performance across all stages — the highest SF in stages 1 and 2, as well as the lowest compressibility from laboratory results — the OS + BC 30% variation is determined as the optimum variation. The phenomenon of decreased effectiveness in OS + BC 35% confirms the existence of an optimum fiber material content which, if exceeded, actually reduces the homogeneity of the mixture [15], [17].

5. Conclusion

This study analyzes the effect of variations in bamboo chip mixtures (0%, 25%, 30%, 35%) on consolidation parameters, embankment stability, and soft soil settlement using numerical modeling software. The consolidation test results show that the addition of bamboo chips is able to decrease the values of Cc and e_0 as well as reduce the consolidation settlement (Sc), with the optimum value obtained in the OS + BC 30% variation (Cc = 0.106; Sc = 0.356 mm). The software modeling results indicate that all mixture variations produce a safety factor (SF) value > 1.5 at all stages, whereas the original soil experiences an SF < 1.5 at the second embankment stage (1.403) and the loading stage (1.490). The OS + BC 30% variation provides the highest SF at the first (2.082) and second (1.723) embankment stages.

All variations meet the allowable settlement rate limit of < 20 mm/year, with a reduction in the loading stage settlement rate of 41.5–49.3% compared to the original soil. Based on the consistency of performance across all parameters, the OS + BC 30% variation is determined as the optimum variation. This research proves that bamboo chips have potential as an economical and environmentally friendly soft soil stabilization material for road embankment construction.

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