

Embankment on Pile: Performance Comparison of Bamboo and Mini Pile for Settlement Reduction and Stabilization of Embankment Over Soft Soil

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SUBMITTED 20 August 2025 REVISED 29 August 2025 ACCEPTED 30 August 2025

ABSTRACT Indonesia's soft soil spreads across islands and it becomes one of the current challenges for newly constructed and existing infrastructure, particularly highways. To construct over it, consolidation and lightweight material methods have been utilized, however, this study will only discuss the embankment on pile method using bamboo cluster piles or mini piles. Based on finite element method (FEM) analysis, the embankment on the bamboo piles or mini piles can reduce settlement and increase the stability of the embankment. In a 30 cm-diameter bamboo cluster pile case, the settlement is reduced as the length/spacing (l/s) ratio increases and the safety factor also increases as the l/s ratio is higher. In terms of the mini pile case, it also has a similar trend where the settlement decreases as l/s increases, although this method has a lower settlement than bamboo. Also, the safety factor using mini pile in a similar l/s ratio is slightly higher than bamboo due to the significant differences in material properties. However, the bamboo material prospect is promising as this material is more sustainable with a smaller carbon footprint to construct than the mini pile counterpart.

KEYWORDS Soft soil; Embankment on pile; Bamboo mini pile

1 GENERAL INFORMATION

Road embankments that are constructed over soft soil face serviceability risk if not treated properly. Lack of treatment or reinforcement can even lead to embankment failure. There are numerous methods that can be adopted to tackle soft soil problems. The methods include: pre-consolidating the soil (Shang et al., 1998), using lightweight embankment (Gunawan, 2020), piled embankment (Himawan *et al.*, 2024), etc. Piled embankment is often ranked the most expensive and also has the highest carbon dioxide (CO₂) emission. A more sustainable alternative is to replace the concrete piles with bamboo piles.

Bamboo is considered a sustainable material. Depending on the species, bamboo can be harvested within 3-7 years after planting (Dransfield, 1995). In comparison to concrete piles, bamboo has a much lower carbon footprint (discussed in next section). In designing bamboo cluster piles and bamboo mattresses, the design considers the potential flood that makes the bamboo material saturated. This condition made the bamboo cluster pile more favorable as the material is more durable if it is fully saturated in the long term (Irsyam, 2018). However, preservatives need to be applied to protect bamboo from degradation (Kumar et al., 1994). Several projects in Indonesia has successfully used bamboo piles as a piled embankment alternative, such as Jakarta Port Terminal Kalibaru, Semarang-Tawang Railway Embankment (Irsyam, 2018), and Semarang-Demak Toll Road, with embankment heights varying from 3-15 m. This study compares the performance of bamboo cluster pile vs. minipile, in terms of stability and the potential reduction of carbon footprint. This study is based on soil data in Semarang-Demak segment of the Central Java highway. Figure 1 shows the study area. Based on the geological map, majority of the area surrounding the study area has soft clay.

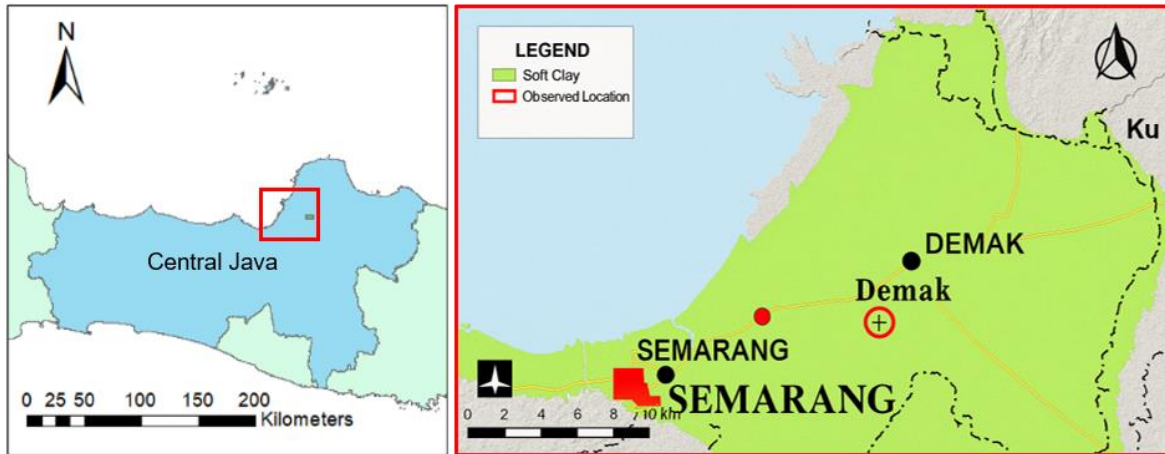


Figure 1. Location of this study (modified from Wardoyo et al., 2019)

2 LITERATURE REVIEW

2.1 Modelling of Bamboo Cluster Pile and Bamboo Mattress

A bamboo cluster pile is a pile composed of tied bamboos. Figure 2 shows a bamboo cluster pile consisting of 7 bamboos. The bamboo cluster piles are installed in grid pattern just like conventional concrete piles. In bamboo system, the pile slab is replaced by bamboo mattress. The bamboo mattress is constructed by stacking multiple layers of bamboo in a criss cross pattern and tying them together (shown in figure 3). The thickness of the mattress depends on the height of embankment fill supported.

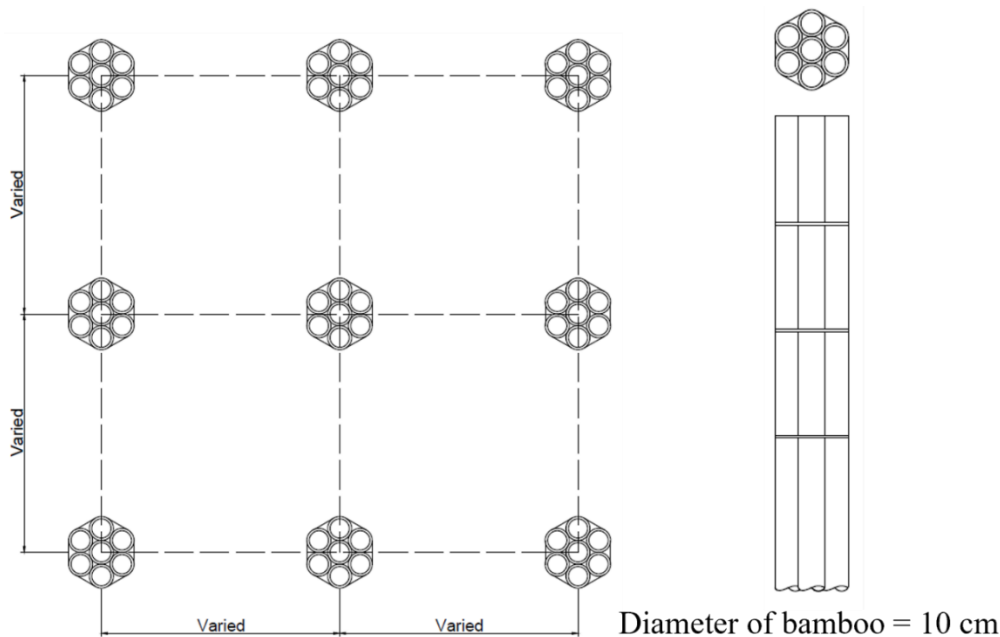


Figure 2. Schematic diagram of bamboo cluster pile (diameter of bamboo cluster = 30 cm)

In finite element, bamboo is modelled as a node-to-node anchor and the bamboo mattress as plates. Thus, bamboo cluster piles can only support axial load without lateral capacity. The required input parameters for node-to-node anchor with elastoplastic material type is the axial rigidity (EA), and the maximum compressive ($F_{\max, \text{comp}}$) and tensile force ($F_{\max, \text{tens}}$) that can be resisted. For embankment construction, the $F_{\max, \text{tens}}$ does not play a role and shall be taken equal to $F_{\max, \text{comp}}$. Subsequently $F_{\max, \text{comp}}$ and $F_{\max, \text{tens}}$ is simply referred to as F_{\max} . F_{\max} is derived from the allowable bearing capacity, i.e., the force required to push the bamboo cluster pile by 10% of its diameter

($\delta_{\max} = d/10$). The spring constant (k) can then be calculated based on Equation 1 and the axial rigidity based on Equation 2.

$$k = \frac{F_{\max}}{\delta_{\max}} \quad (1)$$

$$k = \frac{EA}{L} \quad (2)$$

where k = spring constant (kN/m); EA = stiffness (kN); L = bamboo length (m); F_{\max} = allowable bearing capacity of pile (kN), δ_{\max} = the maximum allowed deformation of the bamboo cluster pile (m) = $d/10$, 3 cm.

Meanwhile, the bamboo mattress is modelled as beam element. The moment of inertia (I) of the mattress and the cross-sectional area (A) of the mattress are calculated and multiplied by the elastic modulus of bamboo to obtain bending stiffness (EI) and the axial rigidity (EA).

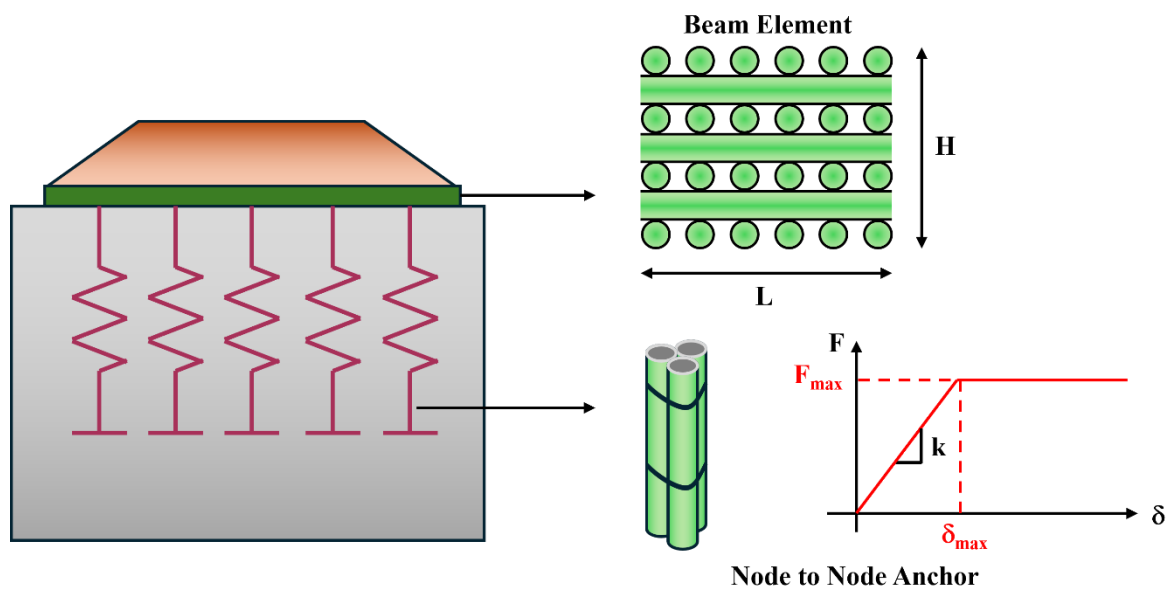


Figure 3. Modelling of bamboo cluster pile and bamboo mattress in 2D finite element (Redrawn from Irsyam et al., 2018); Note: one pair of crisscross bamboo is considered 1 layer, i.e., the 7 stacks of bamboos are counted as 3.5 layers

The bamboo material's mechanical properties of bamboo from previous research are illustrated in Table 1. The bamboo cluster pile is modelled as a node-to-node spring in the finite element. In the parametric study conducted in this paper, the bamboo cluster pile length is varied from 2 to 24 m in 2 m intervals. An additional run with 30 m long bamboo pile is also conducted to investigate the effects if the bamboo were to sit on stiff soil layer. The parameters used for the parametric study are shown in Table 2. As for the bamboo mattress, 5 layers of bamboo mattress are used. The parameters for bamboo mattress are shown in Table 3.

Table 1. Bamboo material mechanical properties (Oka, 2005)

Mechanical characteristics	Experimental strength (MPa)	SNI 2002	
		Mechanical (MPa)	Visual (MPa)
Compressive	50.29	33	4.69
Compressive	51.06	11	0.69
Tensile	402.18	27	4.69
Shear	7.62	5	1.19

Table 2. Stiffness of bamboo cluster pile

Length of pile (m)	P_{ult} (kN)	F_{max} (kN)	k (kN/m)	EA (kN)	Length of pile (m)	P_{ult} (kN)	F_{max} (kN)	k (kN/m)	EA (kN)
2	28.56	14.28	476.0	951.9	16	331.83	165.91	5530.4	88487.1
4	51.18	25.59	852.9	3411.8	18	377.59	188.79	6293.2	113276.8
6	103.01	51.51	1716.9	10301.4	20	423.35	211.68	7055.9	141117.3
8	148.78	74.39	2479.6	19836.9	22	469.11	234.56	7818.6	172008.6
10	194.54	97.27	3242.3	32423.2	24	514.88	257.44	8581.3	205950.8
12	240.30	120.15	4005.0	48060.3	30	711.17	355.58	11852.8	355584.1
14	286.06	143.03	4767.7	66748.3					

Table 3. Bamboo Mattress Parameter

Mattress layer	$I_{mattress}$ (m ⁴)	$A_{mattress}$ (m ²)	EA (kN/m)	EI (kN.m ² /m)	w (kN/m/m)	v
5	0.01419	0.393	3534292	127676.29	1.119	0.3

2.2 Carbon Footprint of Bamboo

Based on several studies, bamboo material can have minimal carbon emissions or even a negative carbon footprint. This study uses a conservative approximation for the bamboo carbon footprint. Constructing a 30-cm diameter bamboo cluster pile can emit roughly up to 4.8 kg.CO₂/m' or 47.98 kg.CO₂ for a 10 m long bamboo cluster pile. The calculation for carbon emission of the installation of a 10 m long and 30 cm diameter bamboo cluster pile is illustrated in Table 4.

Table 4. Carbon emissions from bamboo cluster pile construction

Carbon footprint from Labors (Q ₁)				
Work Items	Duration (Working Hour)	CO ₂ emission (kg.CO ₂ /working hour)	Q ₁ (Carbon Emissions From Labors) (kg.CO ₂)	Reference
Material Lift and Pile Driving	20.95	0.645	13.51	(Lyu et al., 2022)
Total Q ₁ (kg. CO ₂)			13.51	
Carbon footprint from Material (Q ₂)				
Construction Materials	Quantity of Materials	CO ₂ emission	Q ₂ (Carbon Emissions From Materials) (kg. CO ₂)	Reference
Bamboo	0.66 m ³	0.10 kg.CO ₂ /m ³	0.07	(Marchi et al., 2023)
Total Q ₂ (kg.CO ₂)			0.07	
Carbon footprint from Construction Tools (Q ₃)				
Construction Tools and Transport	Quantity	CO ₂ emission	Q ₃ (Carbon Emissions From Construction Tools and Transport) (kg.CO ₂)	Reference
Material Transport*	0.439 t x 100 km	0.516 kg.CO ₂ /t.km	22.70	(Lyu et al., 2022)
Wheeled Loader	0.07 kg	3.10 kg.CO ₂ /kg	0.22	
Hammer Driving Pile	3.7 kg	3.10 kg.CO ₂ /kg	11.47	(Delmag, 2015; Lyu et al., 2022)
Total Q ₃ (kg. CO ₂)			34.40	
Q = Q ₁ + Q ₂ + Q ₃ (kg. CO ₂)			47.98	
Total Q each meter (kg. CO ₂ /m')			4.80	

* Distance from project location is assumed to be 100 km

2.3 Modelling of Minipile

Minipile is commonly used in soil reinforcement, particularly over soft soil. In finite element modelling, the mini pile is modelled as embedded beam rows, as this material can support lateral and axial load. The required input is EA (axial rigidity), EI (bending stiffness), width (b), weight per meter (w), bending capacity (M_p) and axial load capacity (N_p). Table 5 list the parameters for 250 x 250 mm and 300 x 300 mm minipile which are used for the parametric study.

Table 5. Minipile material characteristics (modified from Adhimix PCI Indonesia, 2023)

Mini Pile Type	E (MPa)	b = h (m)	A (m ²)	I (m ⁴)	w (kN/m)	n-strand	M_p (kN.m)	N_p (kN)
250 x 250	30277.63	0.25	0.063	0.00033	1.47	6	43.3	486.4
300 x 300	30277.63	0.3	0.090	0.00068	2.12	6	54.4	765.2

2.4 Carbon Footprint of Minipile

In terms of carbon emissions, the mini pile is significantly higher than the bamboo cluster pile with an estimated 247.96 kg.CO₂/m³ or 1487.77 kg.CO₂ for a 6 m long 300 x 300 mm minipile and 201.52 kg.CO₂/m³ or 1209.14 kg.CO₂ for 250 x 250 mm minipile. These carbon emissions mostly come from concrete, reinforcing bars, and construction. The calculation for carbon footprint of minipile is tabulated in Table 6.

Table 6. Carbon emissions from minipile (300 x 300 mm)

Carbon footprint from Labors (Q_1)				
Work Items	Duration (Working Hour)	CO ₂ emission (kg.CO ₂ /working hour)	Q_1 (Carbon Emissions From Labors) (kg.CO ₂)	Reference
Material Lift and Pile Driving	15.48	0.645	9.98	(Lyu et al., 2022)
Pile Casting	20	0.645	12.90	
Total Q_1 (kg. CO ₂)			22.88	
Carbon footprint from Material (Q_2)				
Construction Materials	Quantity of Materials	CO ₂ emission	Q_2 (Carbon Emissions From Materials) (kg.CO ₂)	Reference
Concrete	0.66 m ³	333.6 kg.CO ₂ /m ³	216.17	(Lyu et al., 2022)
Reinforcement Bars	0.44 ton	2340 kg.CO ₂ /ton	1037.95	
Water	0.16 m ³	0.17 kg.CO ₂ /m ³	0.03	
Total Q_2 (kg.CO ₂)			1254.15	
Carbon footprint from Construction Tools (Q_3)				
Construction Tools and Transport	Quantity	CO ₂ emission	Q_3 (Carbon Emissions From Construction Tools and Transport) (kg.CO ₂)	Reference
Material Transport*	1.296 t x 100 km	0.516 kg.CO ₂ /t.km	66.90	(Lyu et al., 2022)
Production in Plant	20.52 kWh	0.84 kg.CO ₂ /kWh	17.23	
Wheeled Loader	0.0725 kg	3.10 kg.CO ₂ /kg	0.22	
Boiler	51.83 kg	1.90 kg.CO ₂ /kg	98.48	(Delmag, 2015; Lyu et al., 2022)
Hammer Driving Pile	9 kg	3.10 kg.CO ₂ /kg	27.9	
Total Q_3 (kg.CO ₂)			210.73	
$Q = Q_1 + Q_2 + Q_3$ (kg.CO ₂)			1487.77	
Total Q each meter pile (kg.CO ₂ /m ³)			247.96	

* Distance from project location is assumed to be 100 km

3 METHODOLOGY

In this study, the embankment modelled is based on the Semarang-Demak segment. The analysis is conducted using finite element method (FEM). The analysis is used to evaluate the stability of embankment as well as predict the embankment settlement. Two alternatives soil reinforcements are considered: by using 30 cm-diameter bamboo cluster pile and bamboo mattress vs 300 x 300 mm minipile. Based on the soil data, the very soft to soft clay layers have a total thickness of 28 m. The embankment to be constructed in this section has a height of 4.5 m. The embankment slope is constructed at 1V:2H. The parameters for the embankment fill are tabulated in Table 7. The total traffic load is 30.65 kPa, accounting for the pavement load in addition to the traffic load. The embankment and traffic load are activated in plastic conditions, followed by consolidation for 10 years. For more detail, please refer to Kevin (2023).

Table 7. Embankment fill parameters

Material	γ_{unsat} (kN/m ³)	γ_{sat} (kN/m ³)	E' (kPa)	ν	c' (kPa)	ϕ (°)
Compacted fill	17	18	20000	0.3	10	33

3.1 Geotechnical and Geological Conditions

Based on geological maps by the Indonesian Geological Agency (figure 4), the observed location is located above alluvium (Q_a). This formation consists of clay, silt, sand, gravel, plant remains, and boulders of volcanic rocks (Pusat Survei Geologi, 2019). Based on the boring data and standard penetration test (SPT), the observed location is dominated by clay and silty sand.

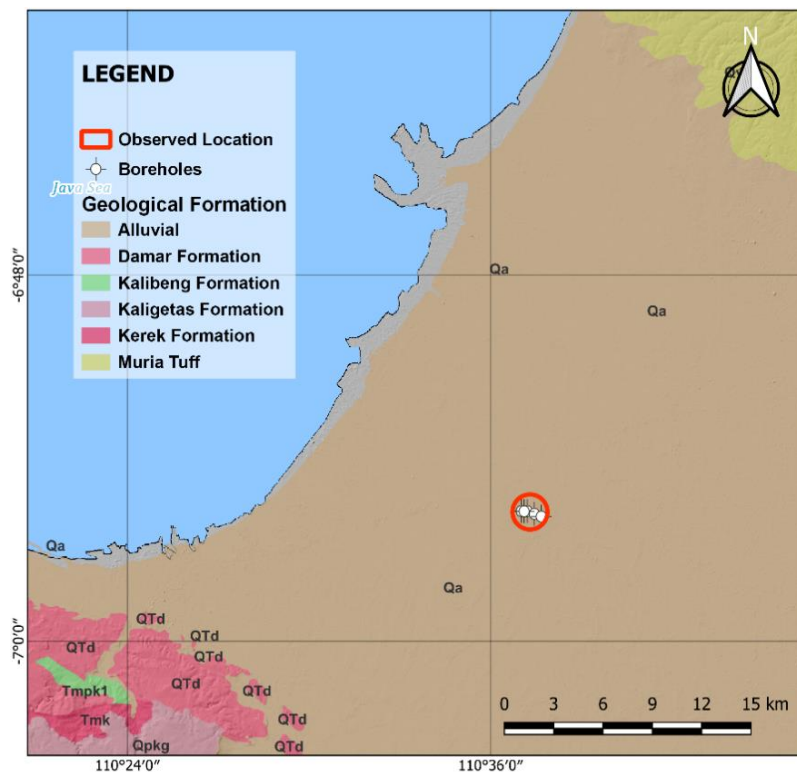


Figure 4. Geological map of observed location (Indonesian Geological Agency/Pusat Survei Geologi, 2019)

A total of 5 boreholes data is available, with the soil stratigraphy shown in figure 5. For the model in this study, BH-PS28 is chosen as it has the thickest, soft clay layer. The average SPT values and soil parameters for each layer is shown in Table 8. The parameters are derived from empirical correlation by Look (2007). The constitutive model used for the clay layers are Mohr Coulomb undrained A, while for the sand layers, Mohr Coulomb in drained conditions are used.

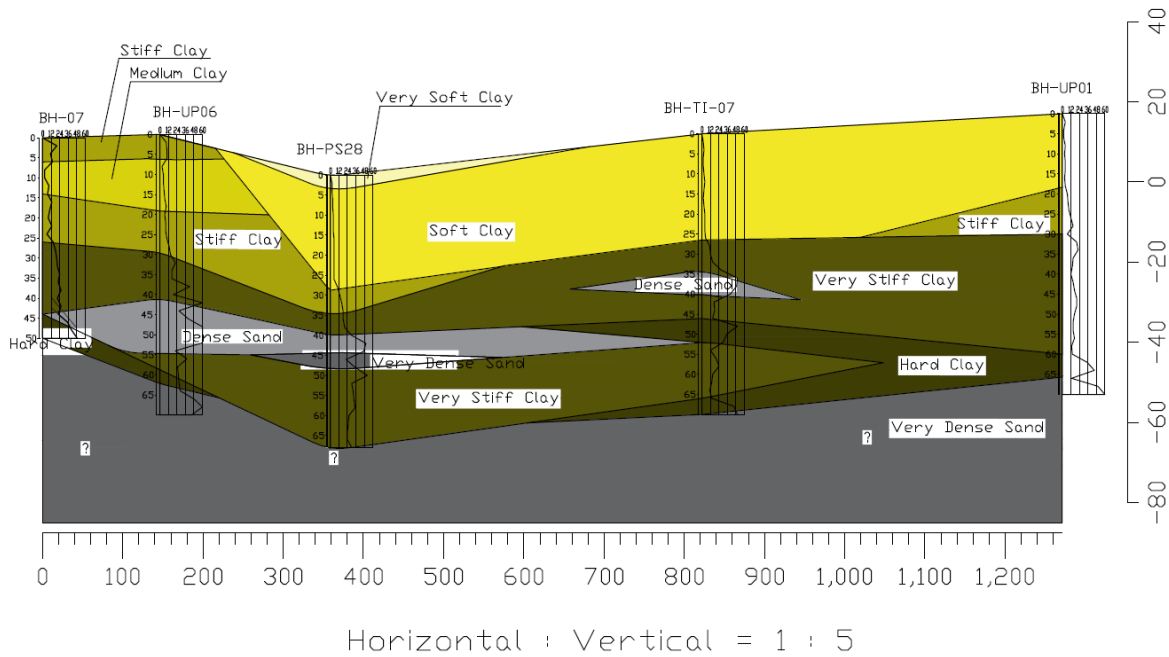


Figure 5. Part of soil stratigraphy for Semarang-Demak segment

Table 8. BH-PS28's soil properties

Depth m	Soil type	Consistency	Average N-SPT	γ_{unsat} kN/m ³	γ_{sat}	E kPa	ν	c' kPa	ϕ' °	k m/day
0-4	Clay	Very soft	2	12	16	3000	0.35	12	1	3.4×10^{-6}
4-28	Clay	Soft	5	12	16	6722	0.35	24.2	1	3.4×10^{-6}
28-36	Clay	Stiff	16	16	18	19375	0.35	81.2	1	3.4×10^{-6}
36-40	Clay	Very stiff	25	16	18	27500	0.35	125	1	3.4×10^{-6}
40-44	Sand	Very dense	49	21	22	59412	0.3	1	47	9.4×10^{-2}
44-48	Sand	Dense	29	19	21	29861	0.3	1	41	9.4×10^{-2}
48-68	Clay	Very stiff	31	16	18	36650	0.35	155.5	1	3.4×10^{-6}

3.2 Parametric Study of Bamboo Cluster Piles and Minipile

Parametric study for bamboo cluster piles and minipile with various configuration are conducted. For bamboo cluster piles, the length of bamboo cluster piles are varied from 2 to 24 m at 2 m interval. An additional run with 30 m long bamboo cluster pile is also conducted to investigate the performance of bamboo cluster pile if it were to sit on stiff soil layer. Other than the pile length, the spacings of bamboo cluster piles are also varied: 1.0 m, 1.5 m and 2.0 m. The bamboo mattress configuration is kept the same for all runs, at 5 layers thick (10 stacks of bamboos). A total of 39 numerical runs for the bamboo cluster piles. Whereas, for the minipiles, three length variations are used, i.e., 6 m, 12 m and 18 m. Three spacing variations, the same as bamboo piles, are used. The runs for minipile are conducted using 250 x 250 mm pile and 300 x 300 mm pile, totaling to 18 numerical runs. The summary of numerical runs are tabulated in Table 9.

Table 9. List of numerical runs

Parameter	Bamboo Cluster Pile	Mini Pile
Diameter/Size	30 cm	250 x 250 mm; 300 x 300 mm
Length	2 to 24 m @ 2 m intervals; 30 m	6 m, 12 m, 18 m
Spacing	1.0 m, 1.5 m, 2.0 m	1.0 m, 1.5 m, 2.0 m
Total Runs	39	18

4 RESULTS

4.1 Embankment Without Soil Reinforcement

Based on a previous study by the same author in the same location (Kevin, 2023), the critical height that can be achieved without any reinforcement is 2.28 m. This is only around half of the design height, which is 4.5 m. Based on this result, soil reinforcement must be conducted to achieve the design embankment height.

4.2 Embankment with Bamboo Cluster Pile and Bamboo Mattress

The results of the numerical runs for bamboo cluster pile are tabulated in Table 10.

Table 10. Bamboo cluster pile embankment - safety factor and settlement

Pile length (m)	Total settlement after traffic operation (m)	Total settlement after 10 years of operation (m)	Settlement after 10 years operation (m)	Safety factor after traffic operation
1 m Pile Spacing				
2	0.198	0.258	0.060	1.480
4	0.195	0.243	0.048	1.575
6	0.186	0.223	0.037	1.693
8	0.175	0.211	0.036	1.740
10	0.164	0.198	0.034	1.806
12	0.156	0.192	0.036	1.847
14	0.142	0.181	0.039	1.961
16	0.132	0.172	0.040	1.981
18	0.137	0.170	0.033	1.912
20	0.123	0.156	0.033	2.098
22	0.117	0.152	0.035	2.062
24	0.115	0.148	0.032	2.077
30	0.056	0.072	0.016	2.594
1.5 m Pile Spacing				
2	0.1977	0.2602	0.0625	1.462
4	0.1967	0.2506	0.0539	1.554
6	0.1915	0.2329	0.0414	1.668
8	0.1833	0.2199	0.0366	1.723
10	0.1723	0.2071	0.0348	1.816
12	0.1608	0.1948	0.0340	1.892
14	0.1508	0.1849	0.0341	1.886
16	0.1415	0.1753	0.0338	1.948
18	0.1329	0.1659	0.0330	2.045
20	0.1262	0.1603	0.0341	1.959
22	0.1195	0.1532	0.0337	1.994
24	0.1055	0.1400	0.0345	2.149
30	0.06525	0.0805	0.0152	2.578
2 m Pile Spacing				
2	0.1978	0.2617	0.0639	1.458
4	0.1975	0.2552	0.0577	1.547
6	0.1942	0.2423	0.0481	1.644
8	0.1885	0.2296	0.0411	1.700
10	0.1796	0.2163	0.0367	1.764
12	0.1694	0.2056	0.0362	1.784
14	0.1589	0.1941	0.0352	1.832
16	0.1491	0.1835	0.0344	1.882
18	0.1378	0.1722	0.0344	1.987
20	0.1312	0.1657	0.0345	1.983
22	0.1205	0.1554	0.0349	2.142
24	0.1135	0.1498	0.0363	2.068
30	0.0762	0.0916	0.0154	2.578

Figure 6, plots the safety factor against the pile length for the three pile spacings considered. The safety factor of the embankment increases at almost a linear rate as the length of the bamboo cluster pile increases. This is because higher embankment load is carried by the pile, reducing the stress transferred onto the soft soil, hence higher safety factor is achieved. In general, tighter bamboo cluster pile spacings have higher safety factors, except when the pile length is 12, 18, 22 and 24 m. This might be due to numerical errors, nevertheless, the trendline shows that 1.0 m pile spacing has the highest safety factor, followed by 1.5 m spacing and 2.0 m spacing. However, there is negligible difference between 1.0 m spacing and 1.5 m spacing.

When the pile length is 30 m, the safety factor for all three pile spacings are the same at around 2.6. The factor of safety is also above the linear trend line. This is because the pile is found on stiff layer (28 m depth). From 8 m till 24 m, the bamboo cluster pile ultimate capacity (P_{ult}) increases by 45.8 kN for every 2 m increment in pile length, but from 24 m to 30 m, the P_{ult} increases by 65.4 kN. This increase contributes to the higher safety factor than the linear trend. The high axial rigidity (EA) of the 30 m long bamboo pile may be enough to carry the embankment load even at 2 m pile spacing, hence the negligible difference in safety factor for all three spacings.

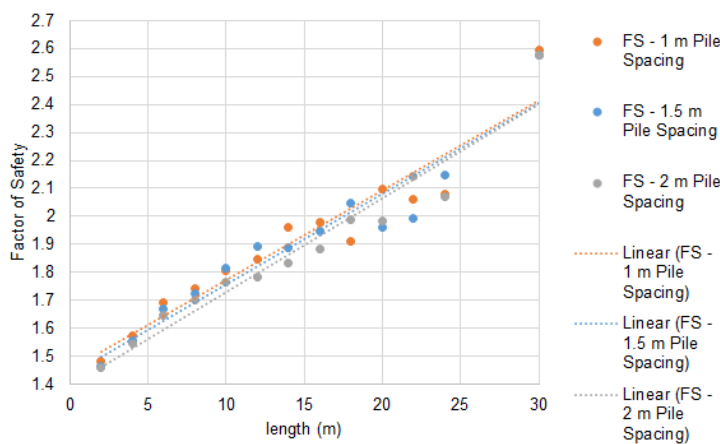


Figure 6. Safety factor of bamboo cluster pile with pile length for various spacings

Based on figure 7, the settlement after 10 years of operation is less than 0.1 m (the value limited by the Indonesian National Standards) for all pile spacing and pile length. As the pile length increases, the settlement reduces, but at a reducing rate. When the pile length is at 10 m, there is no noticeable reduction in settlement when the pile length is further increased. However, when the pile length is 30 m, there is a sharp reduction in the settlement. This is probably due to the load transferred by the bamboo pile when the pile length is 10 m to 24 m is very similar when bamboo pile is modelled with node-to-node anchors. But at 30 m length, there is a noticeable increase in load transferred as the bamboo pile clusters are found on stiff layer.

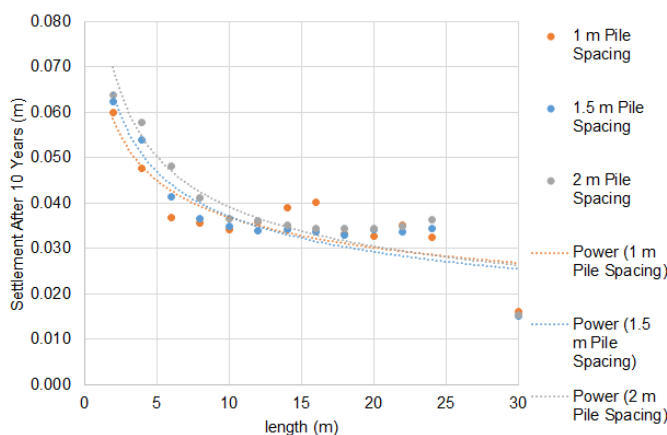


Figure 7. Settlement after 10 years of traffic operation for bamboo cluster pile with various pile spacing

4.3 Embankment with minipile

Based on Table 11 and figure 8, the embankment with mini pile has a similar trend to the bamboo cluster pile. The longer the minipile, the higher the safety factor of embankment. However, different than the bamboo piles which can achieve safety factor > 1.5 with 4 m long bamboo cluster piles, the minipiles cannot achieve the safety factor even with 12 m long pile. This is probably because of the bamboo mattress which is not present in the minipile model. The high stiffness of the bamboo mattress has a significant contribution in increasing the stability of the embankment. Even with only 2 m bamboo cluster pile, the safety factor is close to 1.5. An interesting observation is the influence of pile spacing (both bamboo and minipile) on safety factor. When the pile length is short (< 10 m), the pile spacings have insignificant influence on the safety factor. As the spacing increases, the difference in safety factor between the pile spacings considered can reach 0.2.

Table 11. Embankment with minipile - safety factor and settlement

Pile Length (m)	Spacing (m)	Total Settlement After Traffic Operation (m)	Total Settlement After 10 Years Operation (m)	Settlement After 10 Years Operation (m)	Safety Factor After Traffic Operation
Minipile 250 x 250 mm					
6	1.0	0.2276	0.2568	0.0292	1.285
6	1.5	0.2313	0.2809	0.0496	1.275
6	2.0	0.2338	0.2948	0.0610	1.265
12	1.0	0.1788	0.2018	0.0230	1.460
12	1.5	0.188	0.2065	0.0185	1.425
12	2.0	0.2011	0.2318	0.0307	1.376
18	1.0	0.1383	0.1621	0.0238	1.790
18	1.5	0.1522	0.1683	0.0161	1.636
18	2.0	0.1686	0.1885	0.0199	1.520
Minipile 300 x 300 mm					
6	1.0	0.2352	0.2625	0.0273	1.261
6	1.5	0.2341	0.2807	0.0466	1.267
6	2.0	0.2355	0.2911	0.0556	1.261
12	1.0	0.1883	0.2185	0.0302	1.407
12	1.5	0.1901	0.2084	0.0183	1.409
12	2.0	0.2009	0.2281	0.0272	1.371
18	1.0	0.1447	0.1748	0.0301	1.713
18	1.5	0.1526	0.1703	0.0177	1.635
18	2.0	0.1672	0.1865	0.0193	1.523

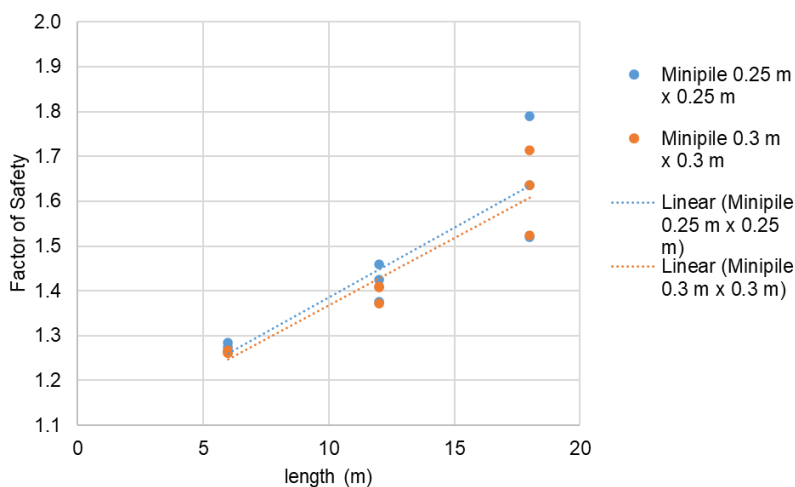


Figure 8. The factor of safety mini pile with various pile spacing

Figure 9 shows the settlement of embankment with minipiles of different lengths, sizes and spacings. In terms of settlement, the embankment on minipiles also achieved the required settlement after 10 years of operation < 0.1 m. The magnitude of settlement is lower than bamboo piles for 12 m and 18 m length, but for 6 m length, the minipiles with higher spacing settle more than the bamboo piles of equal spacing, except for the one with 1 m spacing. This is probably due to the bamboo mattress. At higher spacing, the minipiles are not sufficiently close to carry the embankment load, whereas for the bamboo piles, the bamboo mattress is sufficient to distribute the embankment load.

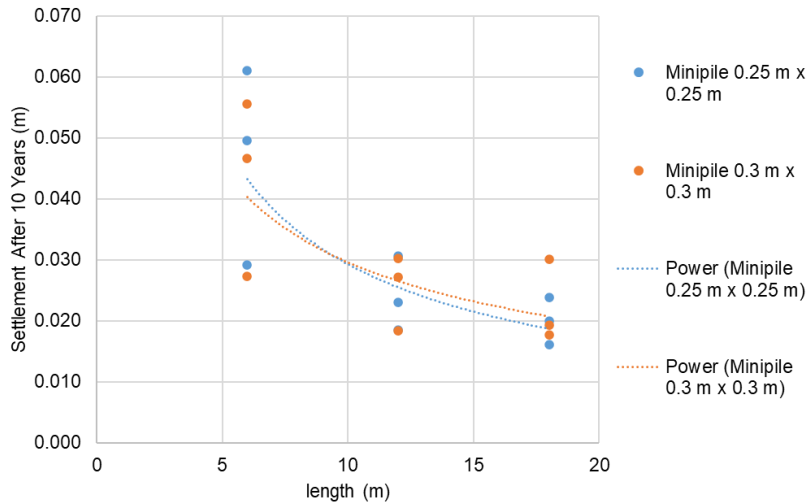


Figure 9. Settlement after 10 years minipile with various pile spacing

4.4 Carbon Footprint Bamboo Cluster Pile and Minipile

Figure 10 and figure 11 shows the carbon footprint for bamboo cluster pile and minipiles with varying pile length and pile spacings. The calculation is based on the embankment width of 51 m and for a 10 m long section. Based on the previous chapter, the carbon emission for the bamboo cluster pile ($d = 30$ cm) and minipiles (300 x 300 mm) is 4.8 kg.CO₂/m' and 247.96 kg.CO₂/m' respectively. There is a huge contrast in the carbon emission (up to 50 times). Considering that bamboo cluster piles can achieve the required safety factor and settlement (Bina Marga, 2017), bamboo cluster piles can serve as a much greener alternative than minipiles. In addition, bamboo material, if submerged and well preserved, can be sustained for a long time. However, minipiles also have their own advantages, such as higher lateral capacity due to its higher tensile strength compared to bamboo.

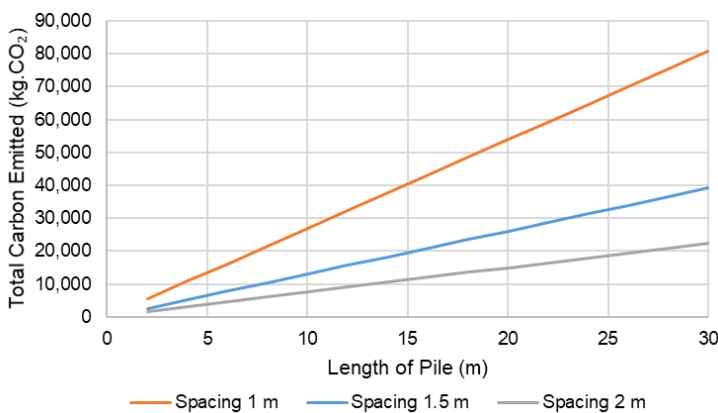


Figure 10. Total carbon emitted for bamboo cluster pile construction

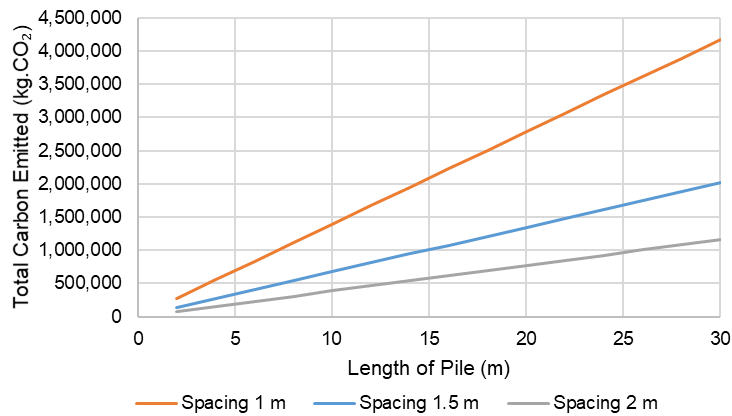


Figure 11. Total carbon emitted for minipiles construction

5 CONCLUSION

In conclusion, the embankment on piles can reduce potential settlement after operation and increase the stability of the embankment. The longer bamboo cluster pile or mini pile is correlated to an increase in the stability safety factor. Also, a longer pile can reduce the settlement after traffic operation. Bamboo cluster pile can serve as a greener alternative to minipiles as it has much lower carbon emission. However, in terms of durability and resistance to lateral load, mini piles are superior to bamboo cluster piles, as bamboo needs to be protected from potential degradation and potential lateral loading.

ASSUMPTIONS AND LIMITATIONS

This analysis neglected the limitation of bamboo material exceeding 10 m long and the financial constraints for construction. The numerical analysis may differ from the real bamboo behaviour as the properties of bamboo are varied and dependent on its species. There are also limitations in terms of numerical modelling, such as soil constitutive model for soft soil, embankment construction time, ignored shaft resistance of bamboo piles, etc. Pile slab that is usually required for piled embankment is also not modelled.

DISCLAIMER

The authors declare no conflict of interest.

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