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Numerical modeling of application of bamboo piles for ground improvement

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ABSTRACT: Settlement is a significant challenge in construction on soft clay. Ground improvement is required to increase the stiffness of soil and to reduce settlement. Bamboo, a rapidly growing and renewable resource, offers a sustainable solution due to its ability to regenerate within a few years, allowing for sustainable harvesting without resource depletion. A bamboo foundation has been proposed to provide a cost-effective option for ground improvement in soft clay. Numerical modeling of the bamboo foundation was carried out by using PLAXIS 3D. The bamboo stiffness, types of bamboo clusters, pile spacing, pile length, and bamboo mattress were analyzed to investigate the effect of these factors on the settlement and load capacity of the bamboo foundation. The results from the analyses showed that the bamboo foundation can be used as a ground improvement in soft clay with its limited capacity.

KEYWORDS: Ground improvement, soft clay, bamboo piles, sustainability, numerical modeling.

1 INTRODUCTION

The presence of a soft clay layer at a construction site has always been a challenge in geotechnical engineering due to its soft and weak characteristics. Loading on untreated soft clay could lead to bearing capacity failure, excessive ground settlement, and instability issues. Therefore, many conventional ground improvement methods such as prefabricated vertical drain, stone columns, and cement mixing are introduced to improve the properties of soil clay (Hou, Ju and Yu, 2014). When the soft clay is found at a deep layer where ground improvement is no longer effective, a pile raft foundation is an alternative solution that bypasses the soft clay and transfers the loading to the competent ground underneath.

Conventional ground improvement methods require long construction periods and high construction costs (Elbadry and Eid, 2018). For light-loaded structures, such methods are not a cost-effective solution. Therefore, practitioners had been looking for alternative solutions. Bamboo is a widely available plantation that grows rapidly and has high carbon sequestration. Therefore, bamboo foundation was found as an innovative, sustainable and cost-effective option for light-loaded structures, especially in tropical regions such as Indonesia (Rahardjo, 2015). Several experimental studies were conducted to test the strength of different species of bamboos and their configurations used in foundations. Those configurations include arrangement of clusters and grids to form a mattress layer (Awalluddin et al., 2017; Ma'ruf, 2017; Widodo et al., 2019). In addition, experiments from researchers (Poulos, 2005; Irsyam, Krisnanto and Wardhani, 2008; Susanti and Waruwu, 2018; Widodo et al., 2019) demonstrated that the settlement of soft clay beneath the embankment of road construction reduced when bamboo piles and mattresses were used as the foundation.

Although the application of bamboo foundation in construction has commenced a few years ago, there is a lack of published numerical studies to analyse the behaviour of bamboo foundation and complement the experimental results. This numerical study is developed to better understand the performance of the bamboo foundation in soft clay.

The objectives of this study are:

1. To back analyse a case study of in-situ bamboo pile load test to obtain the design parameters for numerical modelling;
2. To investigate the pile capacity of bamboo clusters under with different stiffnesses and lengths; and
3. To investigate the effect of bamboo mattress layer on differential settlement of soft soil.

2 METHODOLOGY

This study was carried out using the finite element software, PLAXIS 3D, to simulate the behavior of bamboo foundation under vertical loading in soft clay. Literature review was carried out to obtain a reasonable range of the material parameters of soft clay and bamboo. After that, the in-situ static load test performed by Widodo et al. (2019) was back analyzed to obtain the soil and bamboo properties adopted in the test. Based on this set of parameters and the observed pile bearing capacity from the test, a base numerical model was carried out and followed by parametric analyses to investigate the effectiveness of the bamboo foundation in soft clay.

2.1 *Soft clay and bamboo properties from literature*

Table 1 and Table 2 summarize a typical range of soft clay and bamboo properties collated from several literature (Phien-Wej, Humza and Aye, 2012; Surarak et al., 2012; Gutu, 2013; Sompoh et al., 2013; Kaminski, Lawrence and Trujillo, 2016; Likitlersuang et al., 2018).

Table 1. Typical ranges of soft clay properties.

Properties	Symbol	Value	Unit
Cohesion	c'	0-1	kPa
Friction angle	ϕ'	20-27	°
Bulk unit weight	γ	15.5-16.5	kN/m^3
Saturated unit weight	γ_s	17-18.33	kN/m^3
Reference secant stiffness	E_{50}^{ref}	0.69-0.80	MPa
Reference tangent stiffness	E_{oed}^{ref}	0.635-0.85	MPa
Reference unloading/reloading stiffness	E_{ur}^{ref}	2.07-8.00	MPa
Power exponent of stiffness-stress level correlation	m	1	-
Failure ratio	R_f	0.9	-
Side pressure coefficient	K_o^{nc}	0.55-0.75	-
Undrained shear strength	S_u	10-30	kPa
Initial void ratio	e	2.2-2.6	-
Poisson ratio	v	0.2-0.3	-

Table 2. Typical ranges of bamboo properties.

Properties	Symbol	Value	Unit
Outer diameter	*D*	50-200	mm
Thickness	*t*	5-20	mm
Length	*L*	10-20	m
Density	γ_{bamboo}	500-900	kg/m^3
Elastic modulus	E_{bamboo}	7-40	GPa

2.2 *In-situ static load test*

The in-situ static load test of bamboo clusters performed by Widodo et al. (2019) in a ponding area at a village in Central Java, Indonesia was adopted as the reference of this study. According to the borehole data, the subsoil at the site is primarily soft clay with the SPT N-values ranging from 0 to 2. Three types of bamboo configurations including cluster 3 (i.e. three bamboos in a cluster), cluster 4, and cluster 7 were tested in the tests. Bamboos were tied to form a cluster by using plastic strips. They were installed into the soft soil by using a 63 kg free-falling hammer. A static load test was then carried out to obtain the magnitude of the applied load and the corresponding settlement. For each type of bamboo cluster. three sets of tests were carried out. The force-settlement response of bamboo cluster 3, 4 and 7 was idealized as a bilinear curve in the test study as shown in Figure 1. The ultimate load capacity and corresponding settlement of type of bamboo cluster are summarized in Table 3.

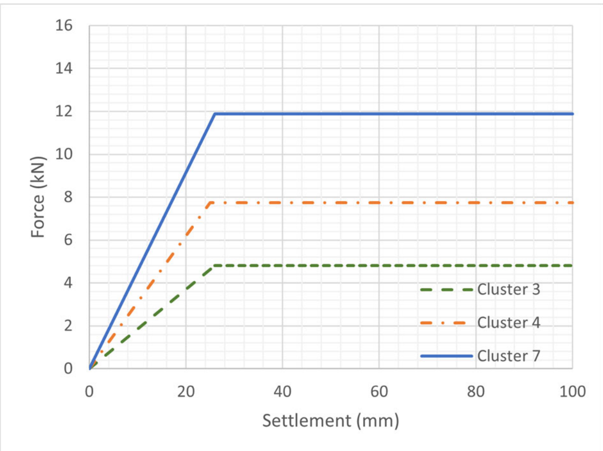

Figure 1. Idealized force-settlement curve from the test study by Widodo et al. (2019).

Table 3. Ultimate load capacity and settlement of the bamboo clusters.

No. of bamboo	Ultimate load capacity (kN)	Displacement (mm)
3	4.8	26
4	*7.8*	25
7	*11.9*	26

3 NUMERICAL MODEL SETUP

3.1 *Soil model*

Hardening Soil (HS), which requires input stiffness parameters of E_{50}^{ref}, E_{oed}^{ref}, and E_{ur}^{ref}, was selected as the soil constitutive model to model the stress-dependent soil stiffness. The drainage type is selected as undrained to simulate the low permeability of soft clay.

3.2 *Structural model*

The study from Engin, Septanika and Brinkgreve (2007) demonstrated that piles modelled by using the structural element type of embedded beam with interface elements produce realistic pile behaviour, especially for piles at a closer spacing subject to vertical loading. With the assigned interface elements, the pile-soil interaction was simulated based on the input interface shear and normal stiffnesses in axial and normal directions, K_s and K_n. These parameters are critical to achieve accurate modelling results, especially for friction piles installed in soft soil, where slippage between the piles and soil can occur.

3.2.1 *Diameter of bamboo cluster*

The bamboo clusters in the forms of 3, 4 and 7 numbers per cluster are shown in Figure 2. As PLAXIS 3D has limitation to simulate the actual bamboo cluster geometry, the cluster was simplified as a single equivalent pile.

In the modelling, the mechanical properties such as the flexural stiffness (k_f) and axial stiffness (k_a) of this equivalent pile shall be the same as those of the actual bamboo cluster. The formulas to calculate k_f, k_a, the moment of inertia (I) and cross-sectional area (A) of the equivalent section and the bamboo cluster are expressed in Equation (1) to Equation (6). Iterations were carried out by utilizing the Excel solver to achieve the targeted condition for the equivalent section. The equivalent section of the bamboo clusters is shown in Table 4 and Figure 3.

$$k_f = \frac{EI}{L} \quad (1)$$

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

$$I_{equivalent} = \pi \times \frac{d^4 - d_1^4}{64} \quad (3)$$

$$I_{cluster} = \sum_{1}^{n} [\left(\frac{\pi(d^4 - d_1^4)}{64}\right) + \frac{\pi(d^2)}{4}\left[\frac{(d^2 - d_1^2)}{4}\right]] \quad (4)$$

$$A_{equivalent} = \pi \times \frac{d^2 - d_1^2}{4} \quad (5)$$

$$A_{cluster} = \sum_{1}^{n} (\frac{d^2 - d_1^2}{4}) \quad (6)$$

Where k_f = flexural stiffness

k_a = axial stiffness

E = Elastic modulus

I = Moment of inertia

A = Cross-sectional area

L = Length of the object

d = Outer diameter

d_1 = Inner diameter

Table 4. Equivalent section of bamboo clusters.

No. of bamboo	Outer Diameter (mm)	Thickness (mm)
3	95.4	14.9
4	*99.5*	20.2
7	*136.9*	25.0

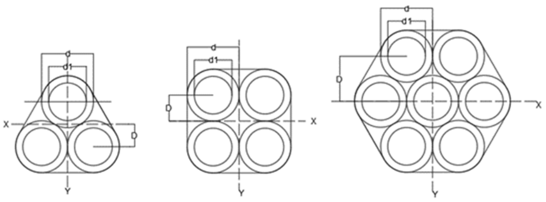

Figure 2. Cross-section of bamboo clusters.

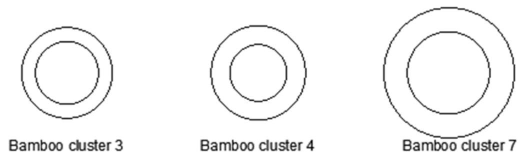

Figure 3. Equivalent section of bamboo clusters.

3.3 *Mesh size*

The mesh of the model was generated with a medium distribution and mesh refinement was enhanced with 1.2 of the global scale factors and 5E-3 of the minimum element size factor. The mesh of the embedded beam was subjected to a 0.5 of the coarseness factors to produce a finer mesh. Therefore, the embedded beam is more sensitive to stress changes in the modelling.

3.4 *Type of Calculation*

As the required output of the modelling in this study is the displacement of the pile, the plastic calculation was selected to perform the elastic-plastic deformation analysis. This calculation method allows for the generation of excess pore water pressures but does not allow for their dissipation. The loading type was set to staged construction, which is controlled by a total multiplier ∑Mstage.

3.5 *Overview of PLAXIS 3D Model Configurations*

Three main PLAXIS 3D model configurations were developed to serve different modelling objectives in this study as described below. However, the pile-soil interaction was kept consistent across the configurations as it is assumed to be independent of the effects of the parameters studied. The soil-pile interaction was selected as linear elastic with the maximum axial skin resistance equal to the ultimate load capacity of the bamboo pile with respect to the type of bamboo cluster discussed in Section 2.2. The base resistance of the pile was set to zero as end-bearing resistance is negligible at the pile tip for the very soft clay.

3.5.1 *Single Pile Model*

A single pile model is developed to back analyse and carry out parametric analysis of the effects of pile-soil stiffness and pile length. The soil model was created as a cube with dimensions of 15m in length, width, and depth to minimize the boundary effects. A pile was modelled as an embedded beam at the center of the soil model based on the typical natural length of bamboo as mentioned in Table 2 above. The single pile model in PLAXIS 3D is presented in Figure 4.

3.5.2 *Pile Row Model*

A pile row model was created to investigate the pile-to-pile interaction in a linear arrangement as shown in Figure 5. Three bamboo piles are spaced equally and embedded in the same soil model as the single pile model.

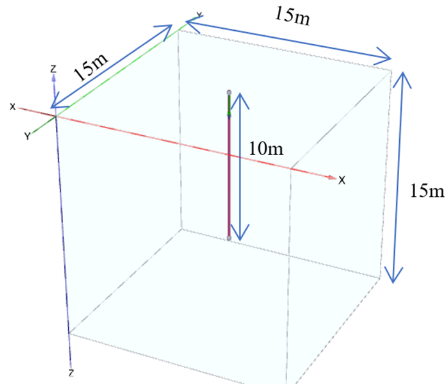

Figure 4. Single pile model in PLAXIS 3D.

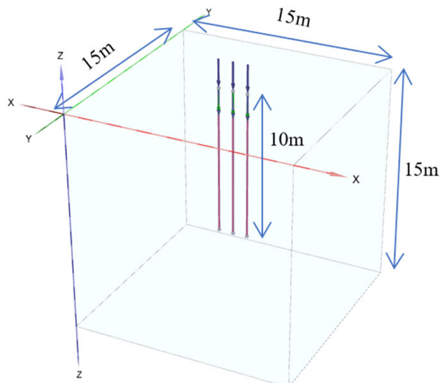

Figure 5. Pile row model in PLAXIS 3D.

3.5.3 *Piles with Mattress Model*

The piles with mattress model is to investigate the influence of the bamboo mattress on the load distribution. The bamboo mattress was modelled as a plate element with a surface load acting on it. The properties of the plate element are listed in Table 5. Figure 6 shows the piles with mattress model in PLAXIS 3D.

Table 5. Input properties of plate element.

Properties	Symbol	Value	Unit
Material type	-	Elastic	-
Unit weight	γ	5.0	kN/m^3
Elastic modulus	E	280	MPa
Poisson ratio	ν	0.3	-
Shear modulus	G	107.7	MPa

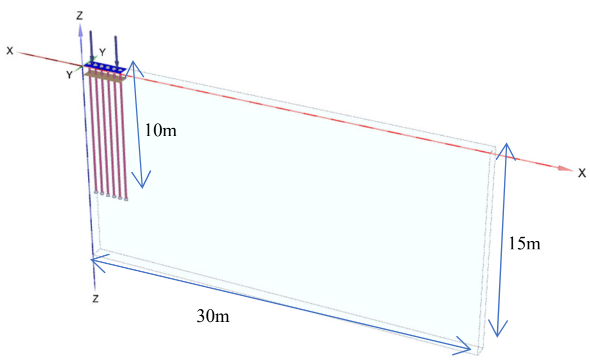

Figure 6. Piles with mattress model in PLAXIS 3D.

4 BACK ANALYSIS OF IN-SITU BAMBOO PILE LOAD TEST

This back analysis is to model the load-displacement behavior of bamboo clusters from the in-situ pile load test and identify a representative set of soil and bamboo parameters, which falls within the range obtained from the literature in Table 1.

A total of 35 test models were carried out by iteratively adjusting 4 key parameters, including the soil stiffness, cohesion, friction angle, and bamboo stiffness to achieve a reasonable agreement between the simulated and measured load-displacement behavior. The range of properties used in the back analyses is presented in Table 6.

Table 6. Range of properties for back analyses.

Properties	Symbol	Range	Unit
Soil			
Cohesion (kPa)	*c'*	0-1	kPa
Friction angle (degree)	*ϕ'*	20-25	°
Reference secant stiffness (MPa)	E_{50}^{ref}	0.69-0.80	MPa
Bamboo			
Elastic modulus (GPa)	E_{bamboo}	0.25-20	GPa

From the parametric analyses, it was observed that changes in soil stiffness, cohesion, and friction angle had a limited effect on the load-displacement behavior, as the range of variation is small. On the contrary, the bamboo stiffness significantly influences the initial slope of the load-displacement curve. The set of calibrated parameters with the closest correlation to the in-situ test data is listed in Table 7. However, it was also observed that the elastic modulus of bamboo obtained from the back analysis is lower than the typical range reported in the literature, as shown in Table 2. The difference may be due to the age and moisture content of the bamboo, as the test was conducted in a ponded area with stagnant water.

From the back analysis results as shown in Figure 7, the numerical modelling results fit well with the in-situ pile load test results. The ultimate load capacities from the modelling are 4.7 kN, 8.1 kN, and 12.1 kN for bamboo cluster 3, bamboo cluster 4, and bamboo cluster 7 respectively.

Table 7. Final calibrated parameters.

Material	Properties	Symbol	Value	Unit
Soil	*Cohesion*	*c'*	0	kPa
	Friction angle	*Φ'*	25	°
	Bulk unit weight	γ	16	kN/m^3
	Saturated unit weight	γ_s	18	kN/m^3
	Reference secant stiffness	E_{50}^{ref}	0.69	MPa
	Reference tangent stiffness	E_{oed}^{ref}	0.69	MPa
	Reference unloading/reloading stiffness	E_{ur}^{ref}	2.07	MPa
	Power exponent of stiffness-stress level correlation	*m*	1	-
	Failure ratio	R_f	0.9	-
	Side pressure coefficient	K_o^{nc}	0.55	-
	Initial void ratio	*e*	2.5	-
	Poisson ratio	*ν*	0.2	-
Bamboo	*Elastic modulus*	*E*	280	MPa

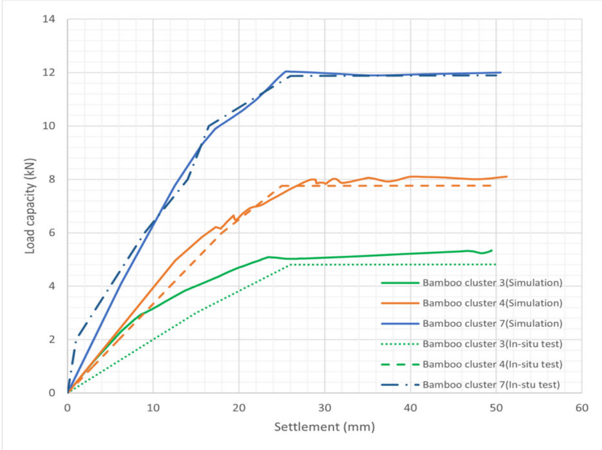

Figure 7. Load-displacement curve of bamboo clusters 3, 4, and 7.

5 RESULTS AND DISCUSSION

In this study, 5 key parameters were investigated, including the number of bamboos in a cluster, bamboo stiffness, bamboo length, bamboo spacing, and the layer of bamboo mattress to evaluate their effect on the load-displacement behavior of the bamboo foundation under vertical loading. The effects on soil-pile interaction and pile-raft interaction were discussed, thereby identifying the effective parameters to increase the performance of bamboo foundation for practical applications.

5.1 *Influence of Pile-Soil Stiffness Ratio on Load-Settlement Behavior*

The stiffness of bamboo piles is determined primarily by the species of bamboo. The bamboo stiffness from 0.25 GPa to 20 GPa was used in the parametric analyses. As soil stiffness and pile stiffness are both key factors in the estimation of pile settlement, the pile-soil stiffness ratio is adopted to evaluate the load-settlement behaviour of bamboo piles. The load-settlement behavior is quantified as the secant stiffness at ultimate load which is defined as the ratio of ultimate load to the corresponding pile settlement. This parameter captures the influence of pile and soil stiffness on the overall behavior at the ultimate load. Figure 8 illustrates that the secant stiffness at ultimate load increases with an increasing pile-soil stiffness ratio. However, the result showed that the influence of pile-soil stiffness ratio progressively decreases when the ratio exceeds approximately 10,000. The gradient of the curve becomes gentler beyond this point, indicating that further increases in pile-soil stiffness have a limited effect on the secant stiffness at the ultimate load for the bamboo pile. This trend is found similar to the behavior of the concrete piled-raft system observed from the study by Elwakil and Azzam (2016) when the pile-soil stiffness ratio increased up to 1000.

5.2 *Effect of Pile Length on Load Capacity*

The natural length of bamboo is approximately equal to 18m according to the study by Mohamed and Appanah (1998). Due to the natural length and splicing techniques of bamboo are not yet established, the load-bearing capacity of bamboo piles is limited. Pile length is a critical parameter to evaluate the maximum load-bearing capacity. In this study, pile lengths of 6m, 8m, 10m, 12m, and 14m were analysed for bamboo clusters 3, 4, and 7. The relationship between the load-bearing capacity and the length of the bamboo cluster 3, 4, and 7 is shown in Figure 9. It is shown that the load-bearing capacity for all bamboo clusters has a similar trend, but the increment of load-bearing capacity of bamboo cluster 7 is relatively larger compared to bamboo clusters 3 and 4. The maximum load-bearing capacity is 17kN for a 14m length of bamboo cluster 7.

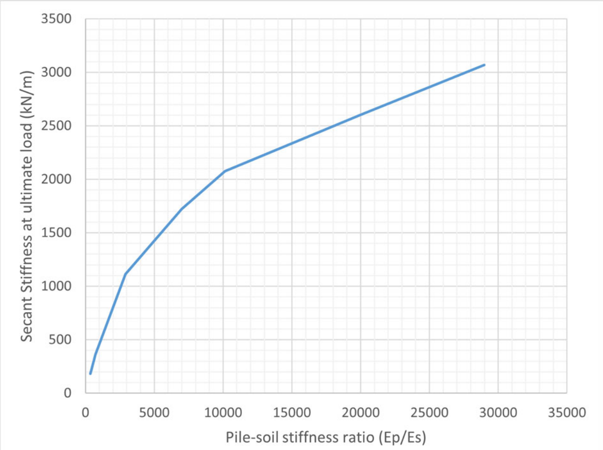

Figure 8. Relationship between secant stiffness at failure and pile-soil stiffness ratio.

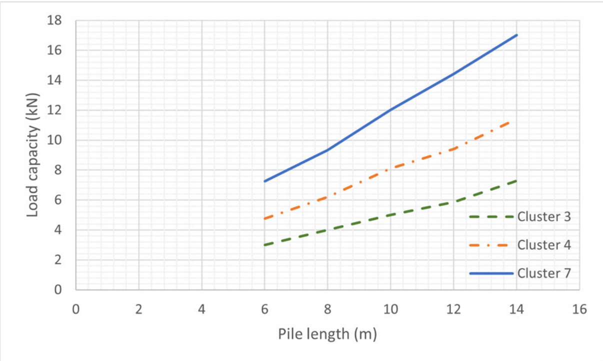

Figure 9. The relationship between load capacity and pile length.

5.3 *Effect of pile spacing on load capacity*

The evaluation of the influence of pile spacing (S) is to determine whether the stress zone of individual piles in a group will overlap which may cause a reduction of the overall load-bearing capacity of the foundation. According to common design practice, the suggested minimum pile spacing is 2.5-3 times the pile diameter (D), i.e. pile centre-to-centre spacing. In this study, the parameter of pile spacing is normalized with the pile diameter, and its relationship to the load-bearing capacity is presented in Figure 11. It is shown that the load-bearing capacity of the piles becomes consistent when the pile spacing ratio is more than 8D. Thus, a minimum spacing of 8D is observed to have almost no group reduction effect and demonstrated the independent pile behaviour in this study.
Figure 10.

5.4 *Effect of bamboo mattress layer on differential settlement*

To reduce differential settlement and improve the distribution of the loading, the piled-raft foundation system is commonly used in practice. Besides the pile spacing, the number of layers of the bamboo mattress is also a critical parameter, which particularly affects the pile-raft interaction. The effect of the number of layers of the bamboo mattress was evaluated by analyzing the settlement at the soil surface resulting from varying the number of mattress layers including 0, 1, 2, and 3 layers. Figure 12 shows the settlement of soil under different layer of bamboo mattress supported by bamboo cluster 7, where the mattresses are vertically spaced at 1m center to center and subject to a 5kPa uniform surcharge. The interface coefficient between the soil and mattress was set as 0.67. The result indicated that the differential settlement at the ground surface is reduced significantly with the bamboo mattresses, especially when the number of bamboo layers is more than 1.

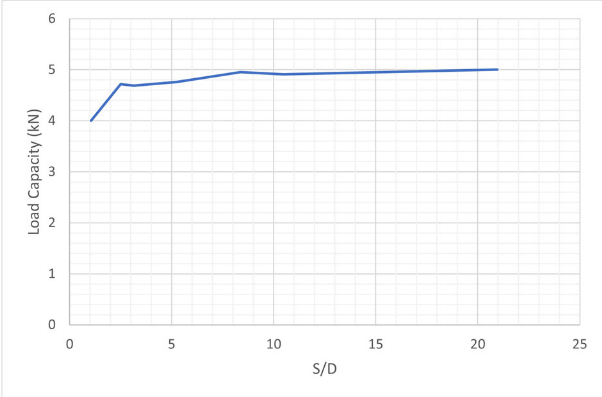

Figure 11. Relationship between load-bearing capacity and normalized pile spacing S/D.

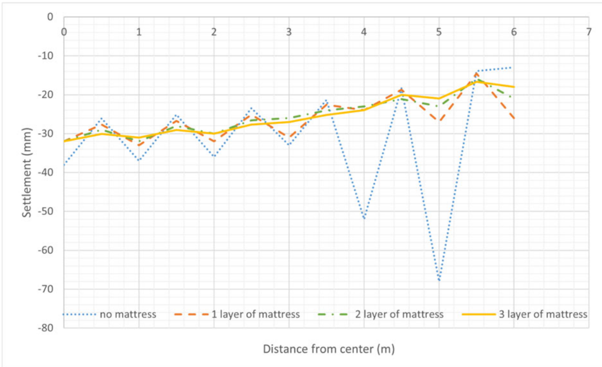

Figure 12. Relationship between settlement at ground surface and layers of bamboo mattress.

6 CONCLUSIONS

Bamboo foundations offer a cost-effective solution for light-loaded structures. With the rapid growth of the green energy sector, many solar farms are now being constructed on soft soils. In such conditions, bamboo foundations present a viable and sustainable alternative. However, there are limited publications on studying and analysing the behaviour of bamboo foundations. Therefore, this study is carried out numerically to understand the performance of the bamboo foundations in soft clay. A back analysis of a case study of in-situ bamboo pile load test was carried out to determine the suitable design parameters for numerical modelling.

Based on the back analysed set of parameters, parametric modelling was conducted to evaluate the effects of bamboo stiffness and pile length on the pile capacity of single bamboo pile. Bamboo piles of cluster 3, 4 and 7 were analysed which showed the ultimate load capacity of 4.8 kN, 7.8 kN and 11.9 kN. The influence of pile-soil stiffness ratio on the ultimate load capacity was modelled. The ultimate load capacity of the bamboo pile system increases when the pile-soil stiffness ratio increases. However, the rate of increase becomes less significant when the pile-soil stiffness ratio is more than 10,000.

Modelling of a pile row subjected to point loads was also carried out to investigate the influence of pile spacing on the pile capacity of bamboo cluster 3. The parametric analyses showed that the load-bearing capacity of the piles is not reduced by the pile group effect when the pile spacing is more than 8D. Influence of additional mattress layers on the ground differential settlement was also investigated numerically. It was found that 3-layer mattresses even out differential settlements better than 1- and 2-layers of mattresses.

In conclusion, the bamboo foundation can provide a feasible, economical, and sustainable solution for light-loaded structures in practice with acceptable settlement limit.

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