

Original Research Article

Reinforcement mechanism and field performance of bamboo pile and bamboo raft foundations for ultra-soft ground in a shallow tidal flat

Yongqiang Ye, Tianxiong Liu *

The First Engineering Co., Ltd. of CCCC First Harbor Engineering Bureau, Tianjin, 300456, China

Abstract: A sea dike expressway across thick marine clay must resist bearing failure during filling and limit the post-construction settlement of the pavement. The paper reports the reinforcement mechanism and the field behaviour of a bamboo pile and bamboo raft foundation below a 3.889 km sea dike expressway on the north coast of Central Java, Indonesia. Bamboo piles 8 m long, each formed from seven culms bound with nylon rope and driven in a 1 m square grid at both toes, act as anchor and anti-slide elements, and a 13-layer bamboo raft about 1.5 m thick carries the surcharge on clay 35-40 m thick. A numerical model gave a peak Mises stress of 5.22 MPa in the piles, an Asaoka analysis of 56 settlement plates gave an ultimate settlement of 2085-4123 mm, and ten inclinometers gave a lateral displacement of 20-230 mm.

Keywords: bamboo pile; bamboo raft; ultra-soft soil; ground improvement; consolidation

1. Introduction

The coastal belt of Java carries a large share of the road network of Indonesia, and alignments on this belt cross thick deposits of soft marine clay. An embankment on such ground develops large consolidation settlement, and the factor of safety against bearing failure stays low long after filling. The Semarang-Demak toll road illustrates the difficulty, because the alignment follows the north coast of Central Java and the roadway also serves as a sea dike against tidal flooding and seawater intrusion.

Ground improvement on soft clay follows several routes. Replacement with granular fill suits thin compressible layers. Thick deposits are treated by staged construction with prefabricated vertical drains and a surcharge fill, and the radial drainage around a drain well was set out by Barron ^[1]. Vacuum preloading applies a negative pressure at the ground surface in place of part of the fill load ^[2], and a trial in Tianjin consolidated clay 20 m thick under a vacuum of 80 kPa ^[3]. A vacuum combined with surcharge reached a vane shear strength about 30 percent higher than an air-booster system in a dredged fill ^[4].

Bamboo offers an alternative where imported fill and synthetic drainage materials dominate the budget. The material grows throughout Southeast Asia and offers a tensile strength close to that of mild steel on a unit weight basis ^[5]. A cluster of bamboo poles driven into soft clay acts as a semi-rigid inclusion, and a bamboo mattress above the cluster transfers the embankment load ^[6]. A biaxial bamboo grid raised the interfacial cohesion of a subgrade from 3.6 to 8.9 kPa with respect to a uniaxial grid ^[7].

Design of a bamboo pile and raft foundation rests on local experience rather than on a quantified mechanism ^[6], and the strain inside the raft has rarely been measured. The present work establishes the reinforcement mechanism of the foundation and quantifies the performance of the system.

2. Project setting and ground conditions

2.1. Project background

The Semarang-Demak toll road forms part of the national strategic projects listed in Presidential Regulation No. 56 of 2018. The alignment runs east to west to the northeast of Semarang, and the road is a dual carriageway with four lanes and a design speed of 80 km/h. The section examined here covers chainage Sta.4+425 to Sta.8+314, a length of 3.889 km, and comprises a sea dike road 3.8 km long, a bridge 0.8 km long, a service area and a toll station. The road relieves traffic congestion between Semarang

and Demak and acts as a wave barrier against tidal flooding and seawater intrusion.

2.2. Ground and environmental conditions

The seabed below the alignment consists mainly of soft clay of low shear strength and high compressibility, with a thickness in the range of 35-40 m. The standard penetration test value stayed at or below 10 within the upper 15 m. The site has a tropical rainforest climate with an annual mean rainfall of about 2270 mm, the significant wave height reaches 2.79 m for a 10-year return period, and the region is subsiding at about 7.5 cm per year.

2.3. Foundation design and settlement criteria

The foundation combines bamboo piles, a bamboo raft, geotextile layers and prefabricated drains. The bamboo piles stand at both toes of the embankment in a square grid at 1 m spacing, and each pile holds seven culms bound with nylon rope over a length of 8 m, with a culm diameter of 7-10 cm. The total quantity reached about 1.1032 million linear metres, equivalent to about 137,906 piles. The bamboo raft sits above the piles and contains 13 layers over a thickness of about 1.5 m. Geotextiles of 200, 400, 600 and 1200 kN/m are laid on the top of the raft and on the top of the first sand fill.

Prefabricated vertical drains penetrate the soft clay at 1.0 m spacing, and a drain is 10 cm wide and 35-56 m long, joined by horizontal drains 30 cm wide at 3.0 m spacing. Filling is divided into six stages, with sand in stages 1 and 2 and selected material in stages 3 to 6, 55 days of standing between stages and 120 days after stage 6. The project adopted the expressway settlement criterion of 10 cm in 10 years in place of the sea dike criterion of 50 cm in 10 years, and the maximum post-construction settlement rate was set at 2 cm per year.

3. Reinforcement mechanism

3.1. Mechanical properties of bamboo

The fibre of a bamboo culm has high strength, the shrinkage is small and the density is low. The tensile strength approaches half of the tensile strength of ordinary steel, and the tensile capacity per unit weight exceeds that of steel by a factor of two to three. The cross section of a culm is annular, with the outer surface of a bend in tension and the inner surface in compression, and the section develops a high bending stiffness. **Table 1** lists the mechanical properties measured for the bamboo used at the site.

Table 1. Mechanical properties of the bamboo used in the foundation.

Property	Value
Tensile strength	1180-2750 kg/cm ² (116-270 MPa)
Flexural strength	785-1960 kg/cm ² (77-192 MPa)
Compressive strength	499-588 kg/cm ² (49-58 MPa)
Tensile modulus of elasticity	87,280-313,810 kg/cm ² (8.6-30.8 GPa)
Flexural modulus of elasticity	55,900-211,820 kg/cm ² (5.5-20.8 GPa)
Elongation	0.0037-0.244
Density	0.67-0.72 g/cm ³ (670-720 kg/m ³)

3.2. Bamboo piles as anchor and anti-slide elements

The top of a pile reaches the seabed level. Bamboo combines a high tensile strength with a bending stiffness and a ductility that suit a point-to-point anchor element, and the design therefore treats each pile as an anchor. A compression zone forms in a layer of finite thickness around a loaded anchor, and anchors at a suitable spacing make the compression zones of neighbouring anchors overlap into a compression band. The loose ground inside the band gains integrity and bearing capacity, and the band forms a reinforced body that carries part of the load. The change resembles the conversion of stacked beams into a composite beam, and the resulting system has a higher bending stiffness and strength than the stacked members.

A pile also passes below the potential slip surface into the stable ground, and the resistance of the

pile balances the thrust of the sliding mass during filling and limits the lateral displacement of the soft foundation.

3.3. Reinforcement combined with consolidation

Placed in the soft clay, the bamboo piles act as reinforcement and form a grid of bamboo bars. The consolidation raises the factor of safety of the embankment to the level required by the design code before the bamboo loses a large part of the reinforcement capacity, and the embankment remains stable on the consolidated soil after the bamboo has decayed.

A numerical model of the composite foundation gave a peak Mises stress of 5.22 MPa, a minimum Mises stress of 0.056 MPa and a peak principal strain of 1.03 percent. The piles near the drain-improved zone bend towards that zone as the ground consolidates, and the extreme strain and shear stress appear in the innermost pile at about one third of the pile length from the embedded end. A layer of geogrid or a short section of bamboo raft placed there would raise the bearing capacity of the composite foundation.

3.4. Mechanism of the bamboo raft

Nylon rope ties the crossing nodes of the raft and the joints along the culms into a single platform that resists the surcharge load and the construction plant. Used as a raft footing, the raft spreads the embankment fill load over a wider area and raises the stability of the soft foundation. A numerical model of the completed embankment showed that the raft redistributed the vertical load and the plastic deformation of the shallow soil became nearly uniform. The plastic strain stayed between the composite foundations on the two sides of the embankment, and the plastic zone did not form an arc at the toe.

4. Laboratory verification of the raft binding configuration

Three laboratory tests established the properties of the bound raft. A bending test measured the flexural response of a raft specimen assembled with the same culm diameters, rope diameter and binding pattern as the field raft, a tensile test on the joint between two culms gave the strength of the connection that transmits the in-plane force through the rope, and a third test in tension gave the tensile stiffness of the raft as a whole. The measured strength and stiffness satisfy the demands that the construction load of the early stage places on the foundation.

5. Strain response of the raft foundation during construction

Strain gauges were installed on the bamboo raft, on the nylon rope and on the geotextile layers. A total of 161 gauges were used, of which 97 were placed on the raft, 42 on the nylon rope and the remainder on the geotextile layers.

The measurements gave four results. The strain reading rose as the height of the fill increased, and the trend was consistent across the gauge positions. During a standing period, when no filling took place, the degree of consolidation and the strain reading rose together, and the internal stress of the raft continued to increase. In the same period the strain increment in the transverse cross section exceeded the strain increment in the longitudinal cross section, and the transverse bamboo therefore carried the larger stress. The gauges rose together across the instrumented area, and the raft acted as a single unit. At location F the gauges reached about 23,000 microstrain in the longitudinal direction and about 16,000 microstrain in the transverse direction, within the elongation range of **Table 1**.

6. Reinforcement effect of the foundation

6.1. Consolidation of the soft clay

The reinforcement effect was assessed on the section between chainage Sta.4+225 and Sta.4+550, which is 325 m long and has an average width of 160 m. Fifty-six settlement plates and four pore water pressure monitoring points were installed in the section. The settlement records were analysed with the observational method of Asaoka ^[8], which treats successive settlement readings taken at a constant time interval as a first-order autoregressive series and obtains the ultimate settlement from the intercept and the slope of the fitted line. **Table 2** gives the prediction at four cut-off dates as filling advanced.

Table 2. Asaoka analysis of the settlement plates at chainage Sta.4+425.

No.	Stage	Cut-off date	Predicted (mm)	Current (mm)	Degree of consolidation (%)	Residual (mm)	Days to 50 %	Days to 90 %
1	1	2023/01/05	415-1865	262.00-861.00	31.26-83.44	86-1004	8-38	13-69
2	2	2023/03/16	1316-2119	1110-2020	84.95-93.93	130-287	36-40	66-68
3	3	2024/01/03	1456-3240	1422-3160	94.26-100	0-102	24-28	50-62
4	4	2024/05/19	2108-4123	1985-3973	93.31-100	0-89	22-27	48-55

The predicted ultimate settlement rose from a range of 415-1865 mm at the first cut-off to a range of 2108-4123 mm at the last cut-off, the residual settlement fell from 86-1004 mm to 0-89 mm, and the degree of consolidation reached 93.31-100 percent. Most of the ground reached a degree of consolidation above the value of 50 percent expected by the design, and the measured rate of consolidation exceeded the simulated rate.

6.2. Groundwater level and lateral displacement

Four standpipes were installed in the monitored section, and the records showed a groundwater level that stayed close to a constant elevation of +0.65 m, taken as mean sea level. The stability of the water level indicates that the drainage and the filling operations did not disturb the groundwater regime around the embankment.

An inclinometer was installed at the outer edge of the embankment at 75 m intervals, and ten inclinometers were placed in total. The lateral displacement of the embankment stayed between 20 mm and 230 mm. The displacement remained small relative to the thickness of the fill placed above the treated layer, and the embankment stayed stable throughout the filling stages and the standing periods. The movement also fell within the control criterion applied to the works, which limits the lateral displacement rate at the toe to 5 mm per day during surcharge preloading.

7. Discussion

The bamboo pile and bamboo raft foundation carried out two duties at the same time. The piles restrained the soft clay at the toes and raised the slope stability during the filling stages, and the raft spread the fill load over the ground. A vacuum combined with surcharge in a dredged fill required a loading period of 308 days^[4], which exceeds the standing period used at the present site.

The transverse bamboo carried a larger stress than the longitudinal bamboo, and the raft therefore needs the same number of culms in each direction. The strain in the raft continued to rise during the standing periods, and the internal stress of the raft follows the consolidation of the ground rather than the fill height alone. The design had allowed 75 days of standing between stages, and the Asaoka prediction supported a reduction to 55 days.

Two limitations apply. The strain gauges recorded the total strain of the raft, and the readings include the effect of temperature and of the installation procedure. The Asaoka prediction depends on the time interval chosen for the settlement readings, and the predicted settlement is therefore a range rather than a single value.

8. Conclusion

The paper reports the reinforcement mechanism and the field performance of a bamboo pile and bamboo raft foundation used to treat ultra-soft ground below a sea dike expressway on the north coast of Central Java.

Bamboo piles of 8 m length, formed from seven culms and installed in a 1 m square grid at both toes of the embankment, act as anchor and anti-slide elements. Anchors at a suitable spacing make the compression zones of neighbouring anchors overlap into a compression band, and the band raises the shear strength and the bearing capacity of the soft clay. The pile resistance balances the thrust of the sliding mass and limits the lateral displacement of the foundation.

A numerical model gave a peak Mises stress of 5.22 MPa and a peak principal strain of 1.03 percent in the bamboo piles, and the extreme value appeared in the innermost pile at about one third of the pile

length from the embedded end. The 13-layer bamboo raft about 1.5 m thick spread the fill load over the ground, and the plastic strain stayed between the bamboo pile composite foundations on the two sides of the embankment.

The Asaoka analysis of 56 settlement plates at chainage Sta.4+425 predicted an ultimate settlement between 2085 and 4123 mm and a residual settlement below 89 mm at the last cut-off. The lateral displacement stayed between 20 mm and 230 mm, and the embankment remained stable through six filling stages. The results support the use of a bamboo pile and bamboo raft foundation for the treatment of ultra-soft ground in a shallow tidal flat.

About the author

* Corresponding author: Tianxiong Liu (1990.01.07) , Male, Han ethnicity, Tang County, Hebei, Bachelor's Degree, No.1 Engineering Co., Ltd. of CCCC First Harbor Engineering Co., Ltd., Senior Engineer, Tunnel Engineering.

References

- [1] Barron, R. A. (1948). Consolidation of fine-grained soils by drain wells. *Transactions of the American Society of Civil Engineers*, 113, 718-742.
- [2] Kjellman, W. (1952). Consolidation of clay soils by atmospheric pressure. *Proceedings of a Conference on Soil Stabilization*, Massachusetts Institute of Technology, Boston, 258-263.
- [3] Chu, J., Yan, S. W., Yang, H. (2000). Soil improvement by the vacuum preloading method for an oil storage station. *Géotechnique*, 50(6), 625-632.
- [4] Liu, J., Li, J., Lei, H., Zheng, G., Jin, Y. (2022). Ground improvement of dredged fills with two improved vacuum preloading methods: Case study. *Journal of Geotechnical and Geoenvironmental Engineering*, 148(12), 05022007.
- [5] Rochim, A., Latifah, K., Supriyadi, B. (2020). Characterization of compression and tensile properties of bamboo Jawa (*Gigantochloa atter*) and bamboo Apus (*Gigantochloa apus*) for application as soil reinforcement. *IOP Conference Series: Earth and Environmental Science*, 498, 012040.
- [6] Widodo, B., Pratikso, Rochim, A., Irsyam, M., Widoanindyawati, V. (2019). Influence of bamboo pile clusters in the pile mattress bamboo construction systems as reinforcement of soft subgrade that support embankment load. *IOP Conference Series: Materials Science and Engineering*, 527, 012055.
- [7] Hu, Y., Chen, S., Xie, C., Zhong, W., Yin, H., Luo, Z., Luo, B., Liang, B., He, M., Huang, J. (2022). Feasibility study on the bamboo grid instead of geogrid for soil-rock mixture subgrade reinforcing. *Materials*, 15(12), 4047.
- [8] Asaoka, A. (1978). Observational procedure of settlement prediction. *Soils and Foundations*, 18(4), 87-101.