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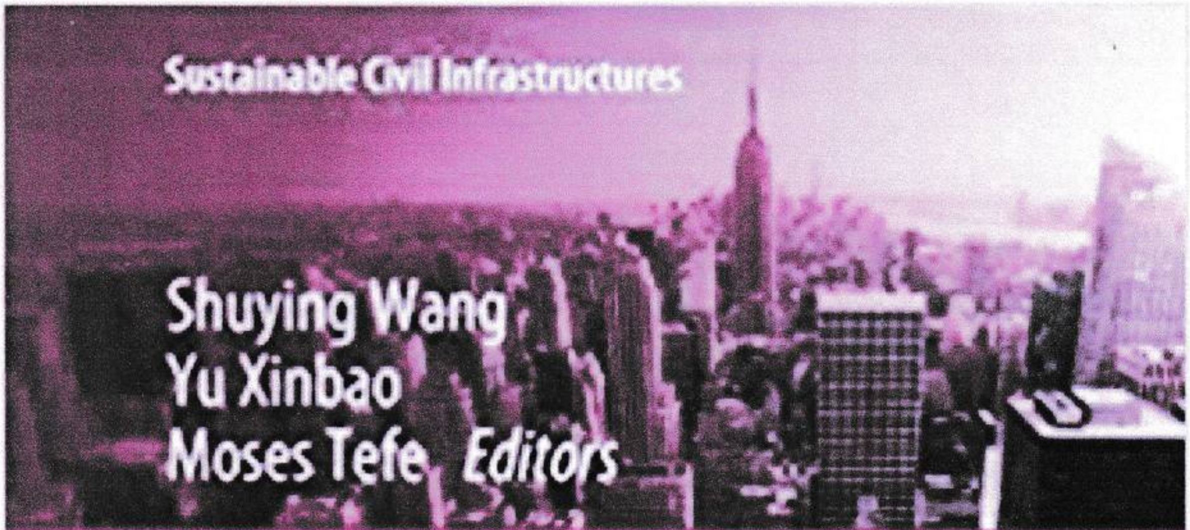


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# New Solutions for Challenges in Applications of New Materials and Geotechnical Issues

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# Numerical Modelling of Reinforced Stone Columns and Bamboo Mattress for Supporting Causeway Embankment on Soft Soil Bed

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**Abstract.** This paper presents numerical model of reinforcement of causeway embankment over soft soil deposit using bamboo grid mattress and stone columns. A series of experimental tests were undertaken to obtain several mechanical parameters of stone columns, and mechanical characteristics of bamboo grid. The soft soil is silty clay in deep layer in which its index and engineering properties derived from oedometer tests. FEM model of a causeway embankment over bamboo grid mattress overlying deep soft soil reinforced by a group of granular columns encased with geotextile, was developed. To validate the FEM model, full scale experimental of similar model was conducted. It was found that FEM model is well agreement with the experimental model. The result explains the stress-strain behavior in bamboo grid mattress and stone columns, interacted with the soft soil as response to increasing embankment height. Bamboo grid mattress enhances the bearing capacity of the soft soil in supporting embankment leading to the decrease of settlements, while stone columns affect the acceleration of consolidation of the soft soil. The results would be beneficial for application of local natural materials such as bamboo for soft soil reinforcement as bamboo is widely available in developing Asian countries.

**Keywords:** Stone columns and bamboo mattress · Soft soil bed
Settlement · Drain · Reinforcement

## 1 Introduction

At infrastructure development in most countries, reliable infrastructures are required within high performance of stability and serviceability. Infrastructures have to be built in cost-effective foundation with sufficient load-bearing capacities and minimum long-term settlement. However, natural condition of lowland areas for infrastructure have become common problem since soft soil foundation in the area can cause excessive settlement which generates undrained failure of the infrastructure. Therefore, proper ground improvements are necessary to undertaken before constructing the infrastructure in order to prevent unacceptable excessive and differential settlement and increase bearing capacity of the foundations (Indraratna et al. 2013). Among other ground improvement techniques, stone column is one of world widely practised since the technique was


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adopted in 1970's in the US. Stone columns can significantly improve bearing capacity, accelerate consolidation, increase slope stability, and control liquefaction (Fatahi et al. 2012). In comparison to other ground improvement such prefabricated vertical drains (PVDs), stone columns are stiffer and faster dissipation of excess pore water pressure from softclay (Basack and Rujiatkamjorn 2016; Guetif et al. 2007). The behaviour of stone column within typical fill embankment is that the total imposed stress can generate the increase of excess pore pressure, progressive settlement of soft clay and arching occurs due to the weight of fill arches over the stone columns (Low et al. 1994; Abusharar et al. 2009; Deb 2010). In such situation, stone columns are combined with geosynthetics reinforcement involving geocells and geogrids. In this study, geosynthetic materials can be alternatively replaced by an innovative and sustainable materials such as bamboo mattress as bamboo is cost effective, environmental friendly material, and posses higher tensile strength compared to geosynthetics (Hedge and Sitharam 2015). Recent study of the use of bamboo as soft soil reinforcement is bamboo cells (Hedge and Sitharam 2015). Even though, such issue of durability of bamboo in the natural condition, bamboo is able to resist towards such weathering in the fully saturated soil. The use of such ecomaterial of bamboo mattress as soft soil reinforcement combined with conventional stone columns remains endeavoured to be investigated. Therefore, this study examines the performance of embankment reinforced with stone columns and bamboo mattress, resting on soft soil bed with fully saturated.

## 2 Full Scale Experiment of Embankment Supported with Bamboo Mattress and Stone Columns

In order to examine the effect on stone columns with bamboo mattress on the performance of embankment on sofy soil bed, a full scale experiment was undertaken. In this way, embankment was constructed on the top of grid system of bamboo used as matrass, and granular columns underlying by soft soil beds (Fig. 1). The soft soil consists of a clay silt layer, underlying by silty clay, clay tuff, and gravel clay. The soft soil is around 4 meters deep, and stone columns were inserted, lying from the top (clay silt) to bottom of the layers (clay gravel). The stone columns are in 0.6 m diameter with 3 m length. Meanwhile, the size of the embankment is 10 m × 10 m × 3.5 m. The granular columns were encased with geotextile non-woven. Totally, stone columns are 16 columns with a 1.8 m space between each column (Fig. 2). The construction of embankment was in three stages, in which settlement measurement undertaken during the stage of embankment filling.

Laboratorium tests were conducted to obtain index and engineering properties of the soft soil, embankment, and stone columns (Table 1).

### 2.1 Measured Settlements of Reinforced and Unreinforced Embankments

Measurements of settlements were undertaken at the embankments within two different conditions such as unreinforced and reinforced embankment. At the unreinforced embankment, stage of construction was started by filling a 0.85 m embankment on the

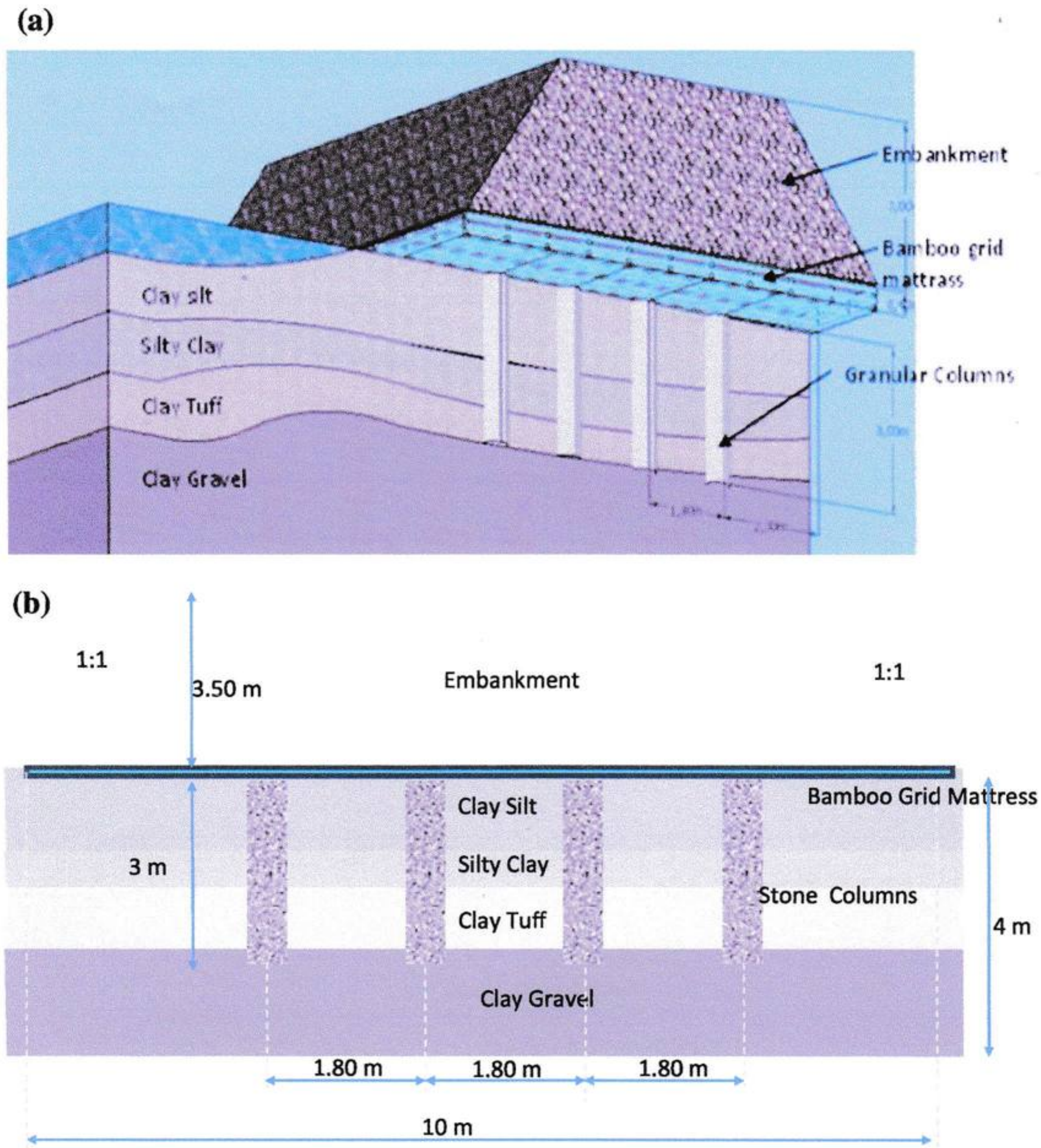


**Fig. 1.** Schematic (a) and cross sectional (b) views of reinforced embankment with bamboo mattress and stone columns.

ground, and the settlement was measured over 24 days. After that, in the second stage, additional 1.10 m thick embankment was laid on the top of the first stage of embankment, and the measurement of the settlement was undertaken for 18 days. In the last stage, 1.20 m embankment was laid on the top, and the observation of the settlement over 24 days (Fig. 3). It can be seen at Fig. 4 that primary settlement due to elastic response of the ground to embankment load was still happened until the end of construction. Total settlement was accounted for 75 cm.

At the reinforced embankment with bamboo grid mattress and granular columns, the first stage is filling 1.30 m embankment of the ground which was already set up with 16 granular columns and bamboo grid mattress. The observation of settlement was over 7 days. The second stage is 1.20 m thick embankment laid on the top of first embankment with a 50 days settlement observation (Fig. 3). At this stage, the consolidation settlement

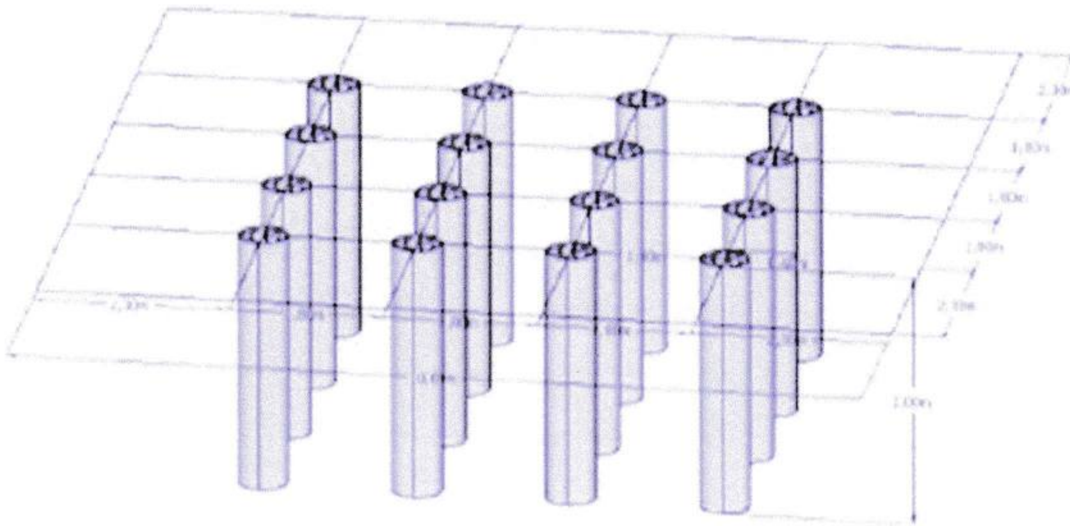

**Fig. 2.** Schematic 3-dimension of stone columns.

**Table 1.** Properties of the silty clay, embankment, and stone column.

| Silty clay | |
|---|---|
| Unit weight, γ, (t/m$^3$) | 1.689 |
| Plasticity index, PI (%) | 59.50 |
| Unconfined strength, qu (kPa) | 32.8 |
| Undrained shear strength, cu (kPa) | 16.4 |
| Effective internal shear angle, ϕ′ (°) | 24.60 |
| Pre-consolidation pressure, Pc (kPa) | 103 |
| Compression index, $C_c$ | 1.107 |
| Void ratio, $e_0$ | 2.987 |
| Consolidation coefficient, $C_v$, (m$^2$/day) | $7.5 \times 10^{-3}$ |

| Embankment | |
|---|---|
| Unit weight, γ, (t/m$^3$) | 1.802 |
| Cohesion, c (kPa) | 0 |
| Internal shear angle, ϕ, (°) | 30 |

| Gravel materials for stone column | |
|---|---|
| Specific gravity | 2.90 |
| Density, (kg/m$^3$) | 2.88 |
| Abrasion, (%) | 23.36 |

was occurred and 90% consolidation can be achieved. The third stage of embankment is 1.10 m embankment with 50 days observation of settlement. Again, 90% consolidation was achieved at several days in the end of construction. Total settlement is 84 cm (Fig. 4). It is obvious that bamboo grid mattress and granular columns can accelerate settlement, and increase of the height of embankment that can be supported by soft soil ground.

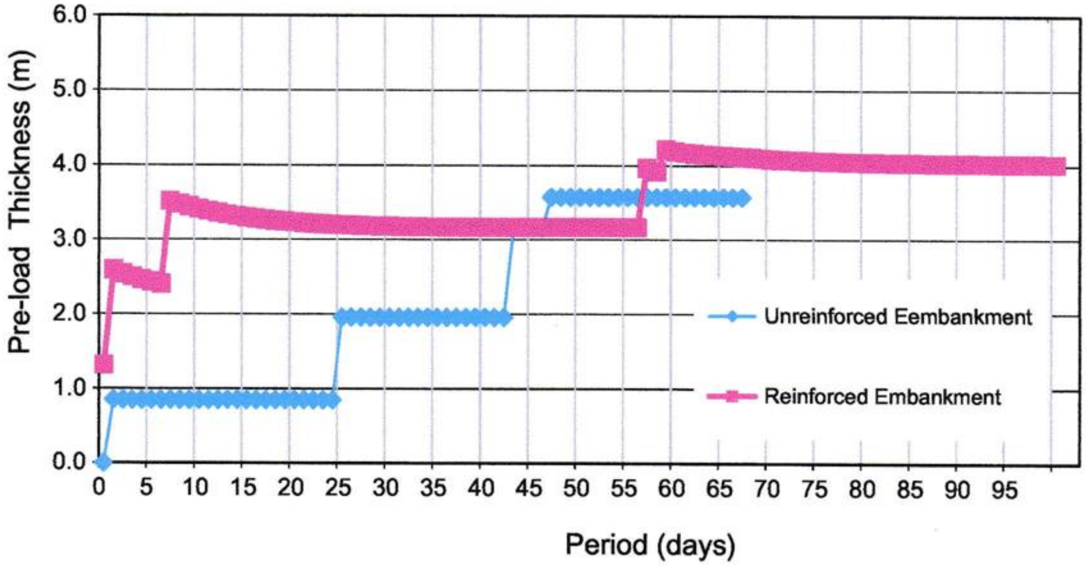


**Fig. 3.** Stage of construction of the unreinforced and reinforced embankment.

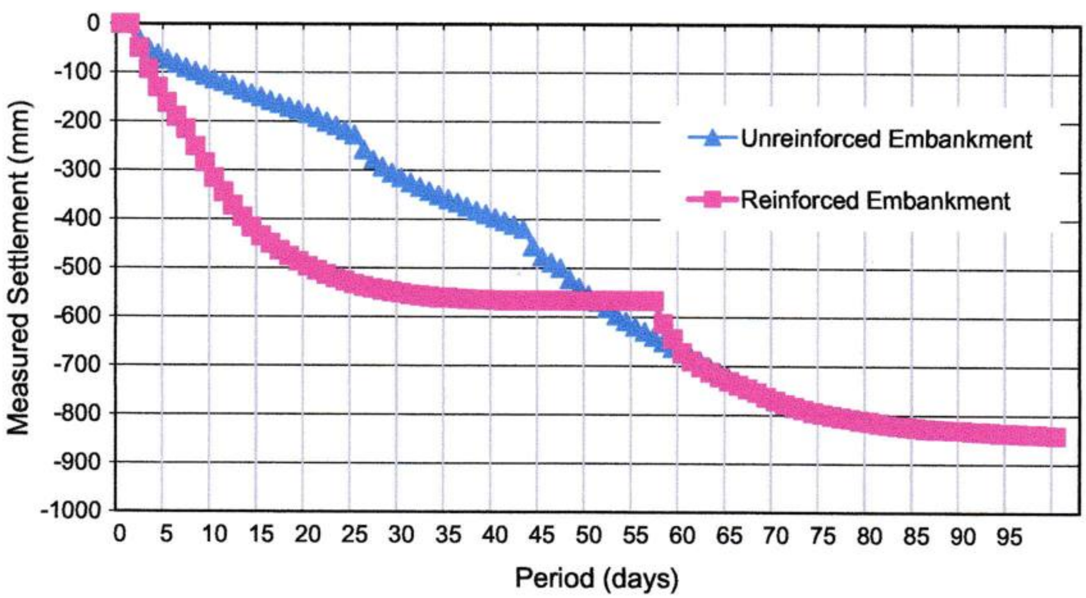


**Fig. 4.** Settlement measurements of the unreinforced and the reinforced embankments.

## 3 Numerical Model of Embankment Supported with Bamboo Mattress and Stone Columns

Analyses of the behavior of the reinforced embankment were undertaken by using FEM modeling of PLAXIS. In this model, soft soil of the ground was modeled as undrained soft soil creep (SSC), while the embankment as Mohr-Coulomb (MC) model. The bamboo grid mattress was defined as plate and granular columns as drained MC.

## 3.1 Mechanical Properties of Geotextile Encased Stone Column

To obtain several mechanical parameters of granular columns such as elastic modulus (E), and Poisson ratio (v), experimental uniaxial tests were undertaken. A stone column with diameter 15 cm and 30 cm height, encased with geotextile, was subjected to axial load (Fig. 5). The stone column was loaded with a load until failure (Table 2). It can be suggested that, based on uniaxial load test. The elastic modulus (E) of the stone column reached at 1317 MPa with Poisson ratio (v) of 0.4. Figure 6 shows the increase axial stress with deformation on the stone column. It must be noted that the geotextile used to reinforce stone column is geogrid with tensile strength of 302 kN/m.

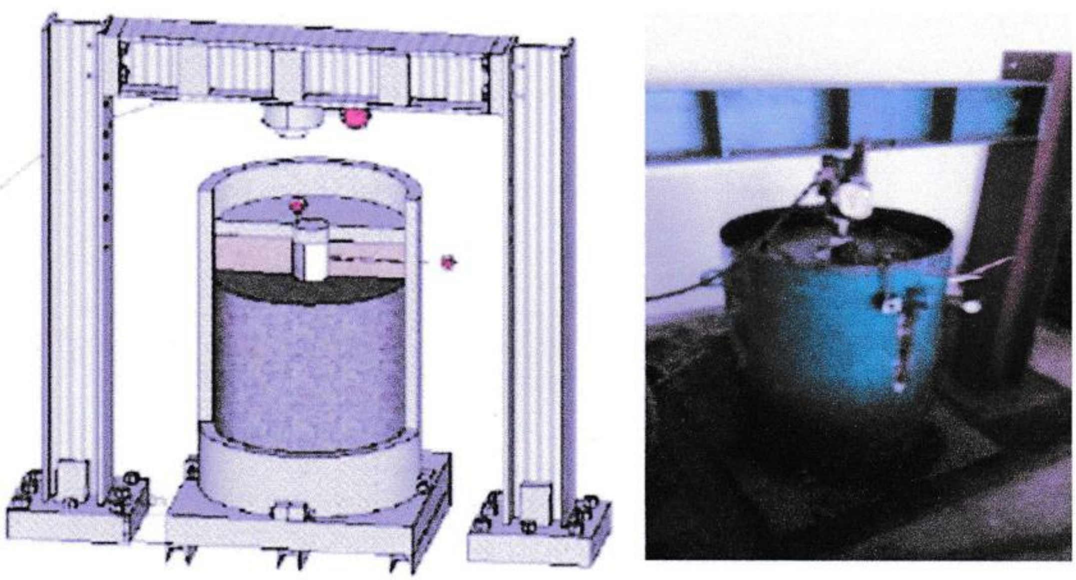

**Fig. 5.** Stone column encased with geotextile was subjected to uniaxial load.

**Table 2.** Stress - deformation on stone column during uniaxial load tests.

| σ (kN/m$^2$) | UCS (Mpa) | $\delta_v$ (mm) | $\delta_h$ (mm) | $\varepsilon_h$ |
|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 |
| 19,782 | 1.12 | 0.0211 | 0.0030 | 0.000140 |
| 22,961 | 1.3 | 0.0261 | 0.0043 | 0.000174 |
| 22431.38 | 1.27 | 0.0267 | 0.0048 | 0.000178 |
| 21724.88 | 1.23 | 0.0267 | 0.0049 | 0.000178 |
| 21018.38 | 1.19 | 0.0266 | 0.0050 | 0.000177 |

## 3.2 Mechanical Properties of Bamboo Mattress

Mechanical characteristics of bamboo grid were obtained through loading tests. There were two loading tests with different loading position. First is load point at perpendicular of bamboo rows, and second is a parallel of bamboo rows (Fig. 7). It can be seen in Fig. 8, ultimate load for Bamboo grid ranges from 38 kN to 59 kN, and maximum deformation

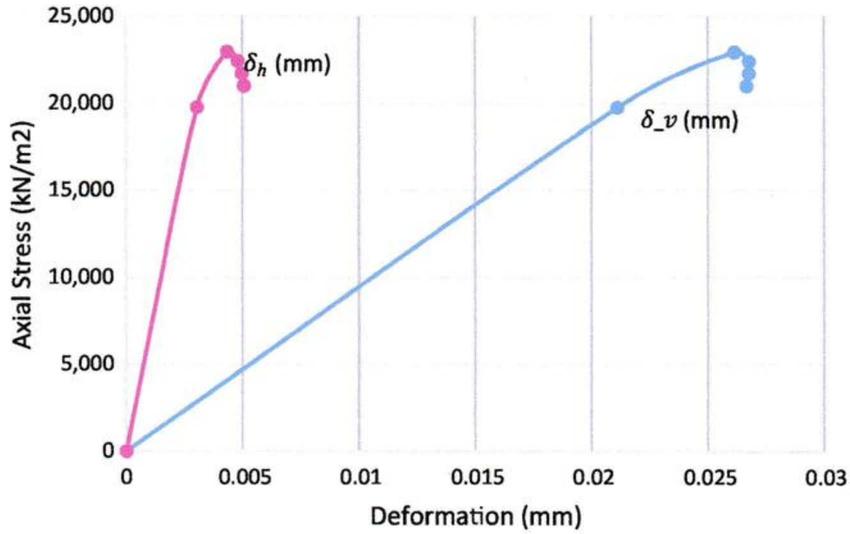


**Fig. 6.** Axial stress vs deformation on stone column under axial load.

is 97 mm. In terms of elastic modulus of bamboo mattress, it depends on direction of loading. It was found that the perpendicular load on bamboo rows generates larger elastic modulus (715 MPa) than the parallel one (460 MPa). Similar result was found in the sample 2, where 693 MPa is at the perpendicular load pattern compared to 497 MPa at parallel load pattern. Based on the results of bending moment tests, stiffness of bamboo mattress can be computed as seen in Table 3.

**Fig. 7.** Loading tests on bamboo mattress.

### 3.3 FEM Model

In the FEM model, the soft soil ground was modelled as silty clay with soft soil creep (SSC) constitutive model, undrained. To compute input parameter in SCC, engineering properties were obtained from Triaxial and Oedometer tests. Based on Coefficient of compressibility (*Cc*) of 1.107 and initial void ratio of 2.987, modified compression index ($\lambda^*$) was computed to be 0.12. Swelling index (Cs) of 0.158 can be used for modified swelling index ($K^*$) at 0.035, and creep index at 0.034 for modified creep

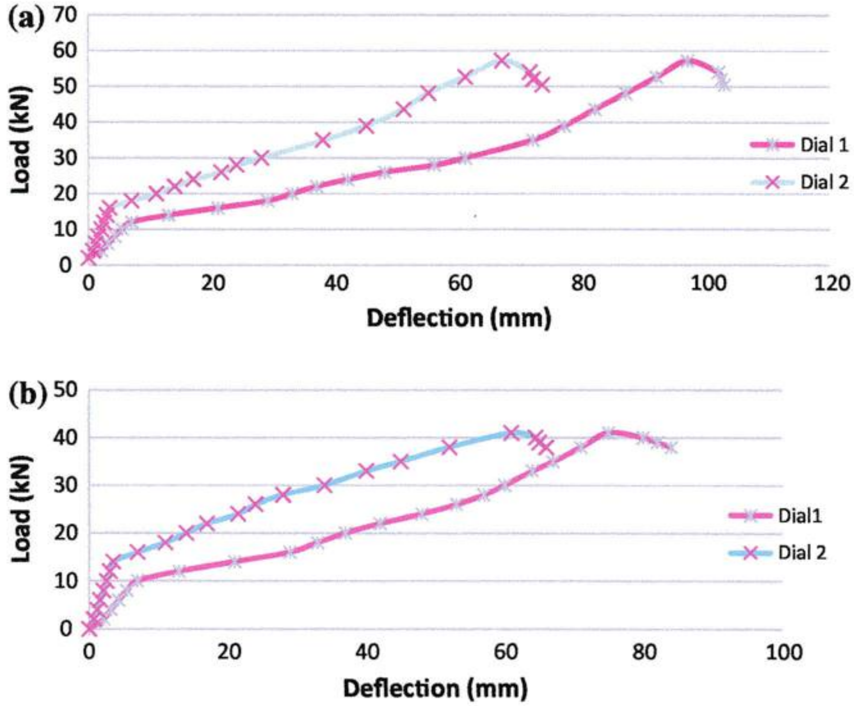


**Fig. 8.** Load vs deflection at bamboo mattress bending moment test with (a) perpendicular and (b) parallel load patterns.

**Table 3.** FEM parameter used for bamboo mattress.

| Material | Type model | Diameter (m) | EI (kN $m^2$/m) | EA (kN/m) | W (kN/m/m) |
|---|---|---|---|---|---|
| Bamboo mattress | Plate | 0.4 | 5563.75 | 414562.56 | 2.640 |

index ($\mu$*) at 0.003. The parameter used for FEM for other materials including stone column, embankment, and bamboo mattress can be seen Table 4.

Since stone column can behave as reinforcement as well as vertical drain, the stone column can be modelled as stone column with vertical drain inside the stone column. To model stone columns as drain, equivalent horizontal drain was then computed by using Hird et al. (1992) equation which is used to transform the insitu 3D unit-cell axisymmetric condition into equivalent 2D multidrain plane strain condition. As a result, horizontal soil permeability at $1 \times 10^{-4}$ m/day was converted to $9.98 \times 10^{-5}$ m/day, assuming no smear zone around the stone column. This value is equivalent to the $6.65 \times 10^{-5}$ m/day horizontal permeability by considering smear zone (Hird et al. 1992). It is noted that the equivalent horizontal permeability without smear zone is larger than that with smear zone. This indicated that the convertion of horizontal permeability in this study is still reasonable.

To validate the FEM model, the similar stage of construction in the field test of embankment without reinforcement was simulated. It was found that the FEM embankment model generates closed result of the simulated settlement (70.4 cm) to the measured settlement (74 cm) in the field (Fig. 9). For comparison, silty clay model with Hardening Soil (HS) was also modelled with several parameters such as $E_{50}^{ref}$ of

**Table 4.** Input parameter for FEM of embankment, and stone column, and bamboo mattress.

| *Stone column* | | |
|---|---|---|
| Constitutive models | MC | [-] |
| Drainage | drained | [-] |
| $\gamma_{unsat}$ | 17.94 | [kN/m$^3$] |
| $\gamma_{sat}$ | 20.68 | [kN/m$^3$] |
| *kx* | 1.0 | [m/day] |
| *ky* | 1.0 | [m/day] |
| $\phi$ | 50 | [°] |
| *c* | 1.0 | [kN/m$^2$] |
| *E* | 1317 | [kN/m$^2$] |

| *Embankment* | | |
|---|---|---|
| Constitutive models | MC | [-] |
| Drainage | drained | [-] |
| $\gamma_{unsat}$ | 17.00 | [kN/m$^3$] |
| $\gamma_{sat}$ | 18.00 | [kN/m$^3$] |
| *kx* | 1.0 | [m/day] |
| *ky* | 1.0 | [m/day] |
| $\phi$ | 30 | [°] |
| *c* | 1.0 | [kN/m$^2$] |
| *E* | 8000 | [kN/m$^2$] |

| *Bamboo Grid* | | |
|---|---|---|
| Model | Plate | |
| *EI* | 5563.75 | [kNm$^2$/m] |
| *EA* | 414562.5 | [kN/m] |
| *t* | 0.4 | [m] |
| *w* | 2.64 | [kN/m/m] |

4300 kPa, $E_{oed}^{ref}$ of 4300 kPa, $E_{ur}^{ref}$ of 14,400 kPa, m of 0.9, and $K_0^{nc}$ of 0.546. The simulations yield the simulated settlement at 70 cm, closed to the measured settlement at 74 cm (Table 5). Overall, the FEM models generate well agreement results to the field test model, indicating that the FEM models is are reliable, particularly for the FEM model with silty clay SSC.

*The Effect of Stone Column and Bamboo Mattress on Settlement of Embankment*

The performance of stone column with bamboo mattress in reducing settlement and accelerating consolidation was examined. In this way, the size of the reinforced embankment model is similar to that in the field test. For reinforcement, the embankment was supported with 3 stone columns, in which each column has a 0.6 m diameter and 3 m length. In the interface between the embankment and the top of stone column, a bamboo mattress with a 10 m length was placed (Fig. 9). The parameter of bamboo mattress is shown in Table 3. The filling of 0.9 m thick first embankment was simulated over 7 days, and then followed by a 1.1 m thick second embankment was simulated over 50 days, and 1.2 m thick third embankment was simulated over

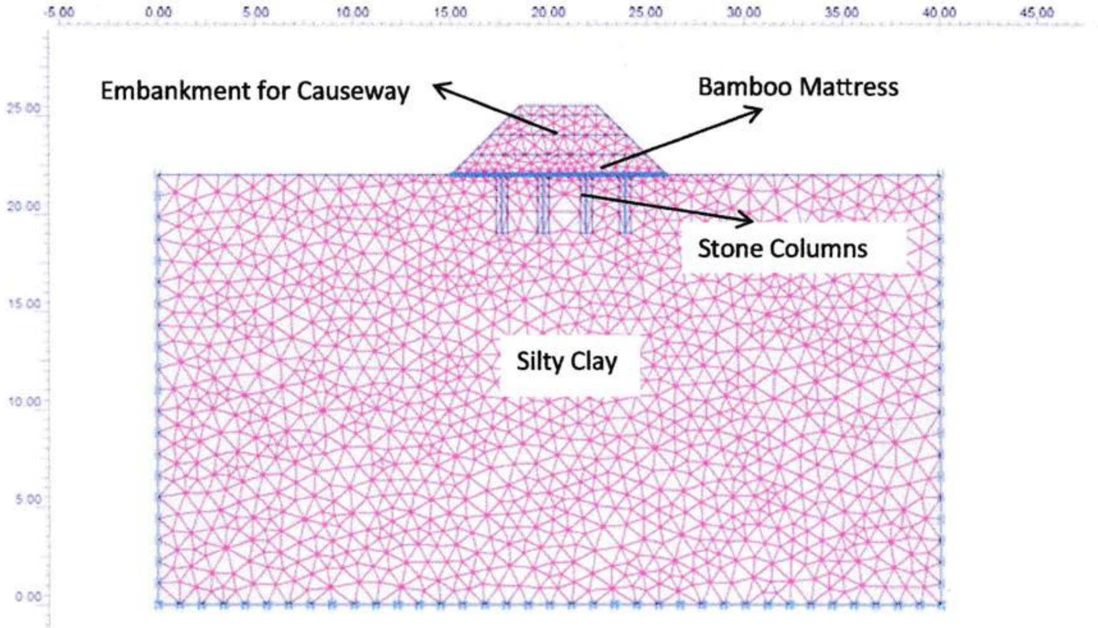


**Fig. 9.** FEM model of the reinforced embankment with stone columns and bamboo mattress.

**Table 5.** Comparison of the simulated settlements and the measured settlement for embankments without reinforcement.

| Soil | Settlement (m) generated in embankment filling at the period | | |
|---|---|---|---|
| | 24th day | 42nd day | 68th day |
| Silty clay HS | 0.02 | 0.08 | 0.7 |
| Silty clay SSC | 0.03 | 0.37 | 0.7 |
| Silty clay in field test | 0.226 | 0.410 | 0.745 |

50 days. For comparison, the embankment was simulated to be supported by the stone columns without the interface of bamboo mattress. This aims to examine the effect of bamboo mattress on settlement of the embankment. It can be seen in Table 6, the stone column with bamboo mattress can accelerate settlement 96.4% faster than the unreinforced embankment. In terms of settlement, bamboo mattress and stone columns reinforcement yield settlement slightly lower than the only bamboo mattress reinforcement, 12 cm compared to 14.9 cm. However, their settlements are about a half (54.6%) to the settlement of the unreinforced settlement. This reveals that stone columns contribute mainly to vertical drain of the soil below the embankment while bamboo mattress increase the soil's bearing capacity. The effectiveness of bamboo mattress can be seen in Fig. 10 that the settlement of the embankment reinforced with stone columns minus bamboo mattress yields remain large settlement (18.9 cm) than other methods. This suggested that the bearing capacity generated by the stone columns is not significant increased.

**Table 6.** Results of the simulated settlements for embankments reinforcement model.

| Embankment reinforcement model | Elastic settlement (m) | Consolidation settlement (m) | Total settlement (m) | Period (days) |
|---|---|---|---|---|
| Unreinforced | 0.122 | 0.104 | 0.226 | 2802 |
| Bamboo mattress | 0.066 | 0.083 | 0.149 | 2644 |
| Stone columns | 0.096 | 0.093 | 0.189 | 977 |
| Stone columns + bamboo mattress | 0.018 | 0.105 | 0.123 | 101 |

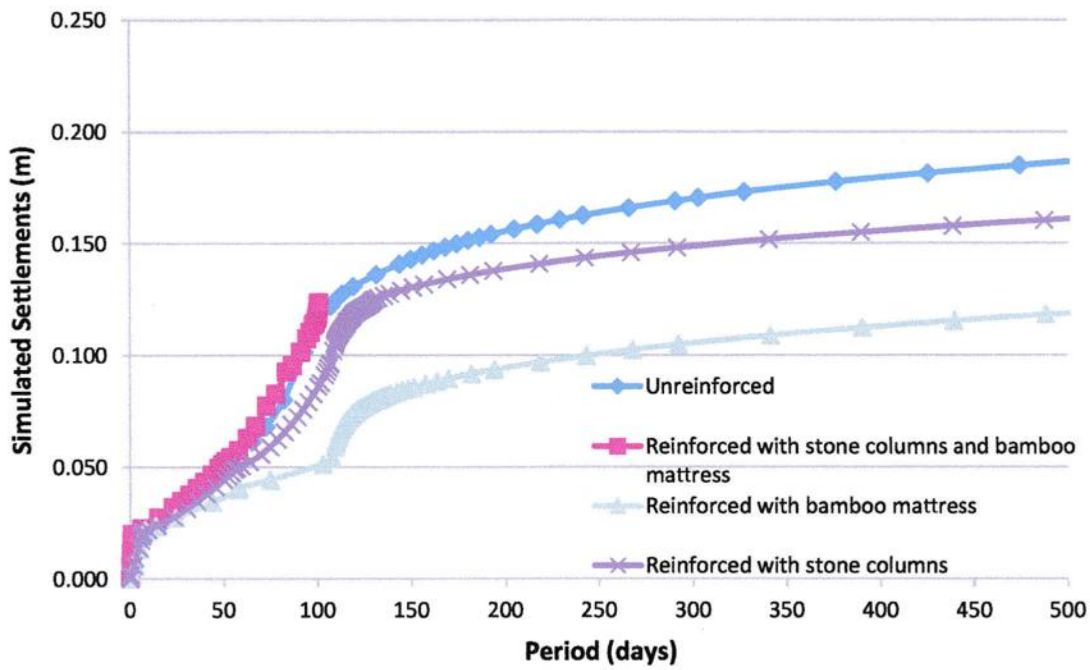


**Fig. 10.** Simulated settlements generated by the model of embankment with alternative reinforcement method.

## 4 Conclusions

1. The use of stone columns would accelerate the settlement by 96% while the use of bamboo mattress would increase bearing capacity a double than that of the embankment without reinforcement.
2. The reinforcement of embankment with combination of stone columns and bamboo mattress seems to be more effective compared to the other methods including the reinforcement with bamboo mattress and the reinforcement with stone columns.
3. Stone columns work as vertical drain while bamboo mattress performs to distribute embankment loads over larger area of the soft soil, leading to the increase of the bearing capacity.

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