Design of Floating Stone Column for Treating Soft Soils

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ABSTRACT:Among the various ground improvement techniques available, vibro replacement is one of the most popular methods that can be used to treat soft soils.End-bearing stone columns are commonly adopted to improve compressible soft soils but shorter, floating stone column may be used as well for a more cost-effective design. This paper mainly describes thedesign aspect offloating stone columnsimplemented at a dockyard facility in Kuching, Sarawak. Empirical calculationbased on the concept of a unit cell was performed to study and understand the settlement performance ofthe stone column installed in soft soils. The efficiency of the stone columnis evaluated by comparingthe magnitude of ground settlements obtained from theoretical results and axisymmetric finite element model. Comparison between theoretical method and numerical model indicates that the finite element modelcanprovidehigher accuracy of the settlementresults of the composite systemas compared to the theoretical calculations.

KEYWORDS: Ground Improvement, Priebe, Rapid Consolidation, Stone Column, Soft Soils, Settlements.

1. INTRODUCTION

Ground improvement using stone columns technique is one of the most commonly used methods for treating soft soils. This treatment is an economic solution that can be used to alter the characteristics of the existing ground conditions to increase the bearing capacity of soft soils, subjected to large loads and to reduce differential and total settlements of the structures constructed on the soft soils (Han and Ye 2002; Raju et al. n.d.).

As reported by Frikha et al. (2014), ground improvement via floating stone columns are deemed to be suitable for improving soft soils include silts, silty sand, and clays to a better state. It is a composite system with higher stiffness and high frictional strength as compared to the natural soils. Besides, the materials used in the construction of stone columns are more permeable than the surrounding soils causing the length of drainage paths to be shortened, thereby speeding up the consolidation process of the surrounding soft soils.

Many researchers have conducted field experiments and numerical studies on the reinforced foundations by using stone columns. Both methods demonstrate that this form of ground improvement technique could accelerate the rate of consolidation of soft soils (Ashmawy et al. 2000; Han and Ye 2001; Han and Ye 2002;Munfakh et al. 1983). Frikha et al. (2014) states that the performance of stone columns has been widely studied through laboratory investigations.

However, only limited researches on the design procedure of stone column for given situations were conducted. Most researchers focused their work on experimental (Afshar and Ghazavi 2014; Cimentada and Costa 2008), theoretical (Balaam and Booker 1981) and field studies(Kirsch 2006; Shao and Gularte 2007) on the behaviour of the stone columns. Black et al. (2007) has presented that the lateral support of the surrounding soils is governing the overall performance of stone columns. Based on Frikha et al. (2014), the performance of stone columns depends on several important parameters such as installation methods, mechanical properties of improved soils and stone material, length of stone columns and area replacement ratio of the improved soils.

According to Alonso and Jimenez (2011), the stone columns design is based on the empirical calculations and contractors' experience. Stone columns are commonly designed to be constructed on hard stratum but shorter or floating columns are adopted in many cases due to construction costs and machine limitations (Ng and Tan 2014).

Priebe's empirical method is the most popular design method among all available methods for designing stone columns in Europe (Priebe 1995). It was used to determine the ground settlement treated with stone columns and this method is based on a unit cell column which considered the column is in plastic state whereas the surrounding soils are in elastic condition. This method is mainly used to design end-bearing stone column and the column material is incompressible(Priebe 1995).This composite system consists of stone columns and surrounding soil that improves non-compactable cohesive soil with well-compacted columns made of coarse grained backfill material. The installation of stone columns is aided by vibration and horizontal displacement of soil which densifies the granular soil and reinforces the surrounding soils (Zahmatkesh and Choobbasti 2010).

Based on Bouassida et al. (2009), it criticised that there is some limitation on the Priebe's method in estimating the settlement of the foundation reinforced by using stone column technique.Besides, all design formulas in Priebe's method are interrelated but some of the design formula is not clearly explained in the Priebe's method. On the other hand, the use of depth factor which depends on the unit weight of soil is required to be further clarified.

The main objective of this paper is to demonstrate the design procedures of end-bearing stone columnusing Priebe's and finite element axisymmetric method. Empirical calculation of a unit cell column is conducted to investigate the displacements of the surrounding soil and stone column so that the performance of the composite system can be understood. Based on the case study, it is clear that Priebe's empirical method is suitable to be used in estimating the settlement of end-bearing stone column but it is not suitable to be used for designing of floating stone column.

2. SOIL CONDITIONS

Vibro replacement via floating stone column method was chosen to improve a dockyard facility to support transient loads of 150 kPa located by a riverbank in Kuching, Sarawak. Soil investigation was carried out to determine the soil conditions before the project commenced. Before the commencement ofground improvement activity, approximately 0.5 m thick of gravel was backfilled followed by another layer of sand with thickness of 0.5 m. These two backfilled layers were compacted to ensure the working platform is stable for machineries to work above the soft soils. However, the site geology mainly comprises of soft cohesive soils approximately 30 m thick as shown in Figure 1.

The top soil layer consists of 2.0 m thick loose sand with SPT N-value of 7 followed by 4.5 m thick soft grey silt layer having SPT N-value of 3. The soft grey silt is then underlain by a layer of firm grey silt with an average thickness of 7.5 m and with SPT N-value of 5. Subsequently, it is followed by 1.5 m thick loose gravelly sand and SPT N-value of 9 is encountered. A layer of firm grey clay was founded in between 16 m to 20 m with SPT N-value of 7 followed by a layer of firm grey silt of 2 m thick with SPT N values of 7 was recorded.

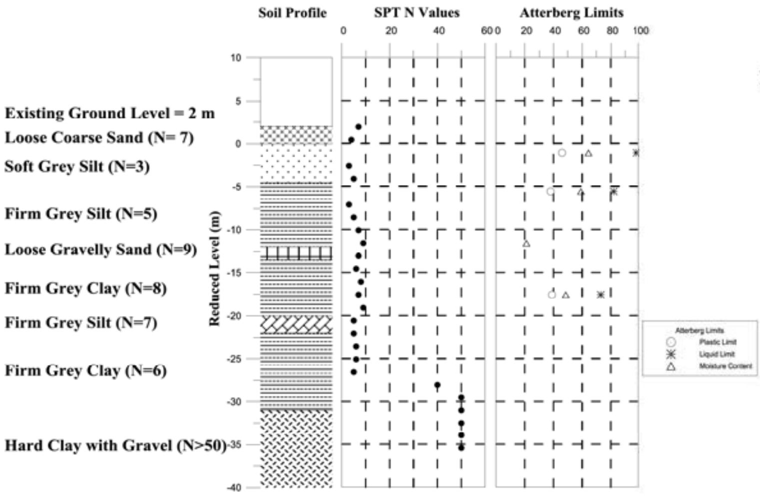


Figure 1.Original Soil Conditions before Ground Improvement Works.

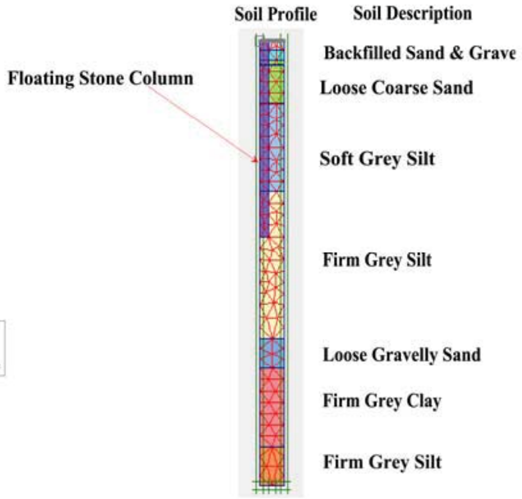


Figure 2.Typical Unit Cell of Floating Stone Column.

Another layer of firm grey clay was founded in between 22 m to 31 m having SPT N values ranging from 5 to 6. Below the firm grey clay is underlain by a layer of hard clay with gravel with SPT N-value more than 50.

Figure 1 shows the SPT N-value with index properties obtained from the field and laboratory tests. As the depth of the soil increases, the SPT N-value and the soil stiffness will increase simultaneously. The typical unit cell of floating stone column with radius of 0.5 m and 10 m deep was modelled using axisymmetric model as shown in Figure 2.

3. DESIGN OF STONE COLUMN USING PRIEBE'S METHOD

According toPriebe (1995), hehas mentioned that stone columns are installed in the soft soil by means of depth vibrator. Nonetheless, the simple investigation method such as soundings will not be able to determine the performance of the installed stone columns and it is not suitable for design purposes. The efficiency of stone columns could be reliably evaluated using theories developedby Heinz J. Priebe.

A unit cell concept was adopted in Priebe's method which assumed the column is in plastic state whereas the surrounding soils are remained in elastic condition. The settlement ofthe single and strip footing supported by limited number of stone column can be easily determined using design charts developed by Priebe. A well-documented case study shown in Priebe (1995)was used as a benchmark for this study and a finite element model was employed in this paper to verify the Priebe's method.As mentioned by Ng and Tan (2014), the performance of stone columns can be evaluated using settlement improvement factor, *n*, which is defined as the ratio of reinforced ground and unimproved ground.

Besides, the input parameters of thecolumn and surrounding soils are tabulated inTable 1 andTable 2, respectively.The friction angle of stone column which fallswithin the range of 35° to 45°can be used to design stone column as recommended by Priebe (1995).In this study, the friction angle of 35° was adoptedwith the dilation angle of 5° ($\psi = \phi$ - 30°) and the Young's modulus of stone column was determined using linear regression of slope of unloading curves(Sim et al. 2015). However,the soil strength parameters (c' and ϕ') summarised in Table 2weremainly derived from another project site with similar soft soil depositsand therefore, they are realistic values to be used. The Young's modulus is 2 times of the SPT N-value (2.0N MPa).

The maximum foundation pressure, P = 225 kN/m^2 was adopted in this study where the design procedures of the stone column was further explainedinPriebe (1995).All calculated results are summarised in Table 3 where the cumulative settlement for treated layers is tabulated in Table 4.

4. FINITE ELEMENT METHOD – AXISYMMETRIC MODEL

Plaxis 2D Version 9 finite element software is used in this study for the analysis of the deformation and settlements of a unit cell stone column. 15-noded triangular elements were adopted to increase the accuracy level in data generation whereas medium mesh was selected as the global coarseness of the model. However, the reinforced area was refined as higher stresses and displacements were expected at the column area. The unit cell column and surrounding soils were modelled as half due to the symmetry where the vertical axis passes through the centre of the column. Based on Balaam and Booker (1981), the column consists of a diameter of influence zone, d_e written in Eq. (1).

$$d_e = c_g s_c \quad (1)$$

wherec_g is the geometry-dependent constant having values of 1.05, 1.13, and 1.29 for triangular, square and hexagon, respectively and s_c is the drain spacing.

Table 1.Stone Column Properties.

Density, γ (kN/m^3)	20.0
Young's Modulus, E (kPa)	120,000
Friction angle of column, ϕ'$_c$ (°)	35.0
Cohesion, c' (kPa)	15.0

Table 2.Input Parameters of Surrounding Soils.

Layer No.	Name	Depth (m)	Column Diameter (m)	A/Ac	E (kPa)	γ (kN/m^3)	Poisson Ratio, μ_s	Phi (°)	C' (kPa)
1	Backfill Sand (SPT 3)	0.5	1.0	7.94	6,000	18.0	0.30	30.0	2.0
2	Backfill Gravel (SPT 10)	0.5	1.0	7.94	20,000	20.0	0.30	30.0	15.0
3	Loose Coarse Sand (SPT 7)	2.2	1.0	7.94	14,000	18.0	0.30	30.0	5.0
4	Soft Grey Silt (SPT 3)	4.5	1.0	7.94	6,000	17.0	0.30	28.0	0.0
5	Firm Grey Silt (SPT 5)	7.5	1.0	7.94	10,000	17.0	0.30	28.0	0.0
6	Loose Gravelly Sand (SPT 9)	1.5	-	-	18,000	18.0	0.30	32.0	5.0
7	Firm Grey Clay (SPT 8)	4.0	-	-	16,000	16.0	0.30	0.0	40.0
8	Firm Grey Silt (SPT 7)	2.0	-	-	14,000	17.0	0.30	28.0	0.0

Table 3.Summarised Output of Each Soil Layer.

Layer No.	n_0	n_1	m_1'	ϕ_1 (°)	c_1 (kPa)	f_d	n_2	m_2'	ϕ_2 (°)	c_2 (kPa)
1	1.538	1.159	0.137	30.723	1.726	1.007	1.167	0.143	30.755	1.713
2	1.538	1.147	0.128	30.675	13.080	1.009	1.157	0.135	30.714	12.969
3	1.538	1.151	0.132	30.694	4.342	1.032	1.188	0.159	30.834	4.207
4	1.538	1.159	0.137	29.026	0	1.061	1.230	0.187	29.391	0
5	1.538	1.156	0.135	29.012	0	1.030	1.191	0.161	29.199	0

Table 4.Calculated settlement of composite system under infinite load area.

Layer	Cumulative Depth (m)	CalculatedSettlement (mm)
1	0.5	8.130
2	1.0	2.417
3	3.2	15.607
4	7.7	77.077
5	10.0	22.899
Cumulative Settlement		**126.13**

Figure 3shows the different arrangement patterns of the stone columns. The column radius adopted in this numerical model is 0.5 m with an influence radius of r_e of 1.41 m and all columns are arranged in square pattern. The boundary conditions of the model are fixed at the base, while the horizontal deformations along the vertical boundaries were restrained. This can be done by selecting the standard fixities option in Plaxis 2D software.

In this axisymmetric model, a uniform distributed load was loaded on a 30 mm thick steel plate on an infinite load area above the stone column. For simplicity, the self-weight of the steel plate is not considered and the load is assumed to be vertically applied above the steel plate. All parameters as shown inTable 1and Table 2are used to model the composite system with the surrounding soils.

Mohr-Coulomb yield criterion was adopted to model granular materials associated with dilatancy angle, $\psi = \phi - 30°$ (Bolton 1986) for $\phi > 30°$ i.e. $\psi = 5°$ for $\phi = 35°$ was utilised to model the well-compacted granular materials (stone columns). However, hardening soil model was selected to model soft clay layer. Moreover, the gravel is assumed to be tightly interlocked with the surrounding soil due to compaction where the interface elements can be eliminated as the bonding of this composite system is almost perfect (Tan et al. 2014). Hence, the interface elements are not considered in this study to simplify the analysis.

The axisymmetricnumerical model wasused to simulate the end-bearing effect of a reinforced ground with stone column and will be subsequentlyvalidatedagainst Priebe's theoretical result. The theoretical result is tabulated in Table 4 whereas the numerical settlement is shown in Figure 4.Figure 4(a) and (b) show the deformed mesh and total displacements of the reinforced ground, respectively. Both theoretical and numerical results show good agreements which proved that the ability of finite element method to resemble the behaviour ofstone column under loadings. The maximum difference in immediate settlement recorded between these two methods is approximately 5 mm.Therefore, the overall understanding of the end-bearing stone column can then be validated.

Upon validation of the end-bearing stone column, a floating stone column is modelled using axisymmetric function in finite element method as shown in Figure 2. This soil modelis based on the soils located bya riverbank in Kuching where soft soils are reinforced using floating stone column technique.The floating stone columns were installed with the 1 meter diameter and 10 meter depth with thearrangementof 2.5 meter square grid from centre to centre. The results of the floating stone column generated in finite element method will be discussed later.

5. RESULTS AND DISCUSSIONS

As mentioned previously, verification of the end-bearing stone column using finite element method has been done by comparing the results with Priebe's method. Subsequently,the floating stone column was modelled using Plaxis 2D software to study three-dimensional axis-symmetric effects of the column installed in soft cohesive soils. Consolidation analysis function was selected in finite element software for this study to perform back-analysis using the numerical model of a unit cell stone column installed in soft soils. The width of the soil model is based on the equivalent radius of the square pattern which is 1.41 m wide inclusive of 0.5 m of a unit cell column.

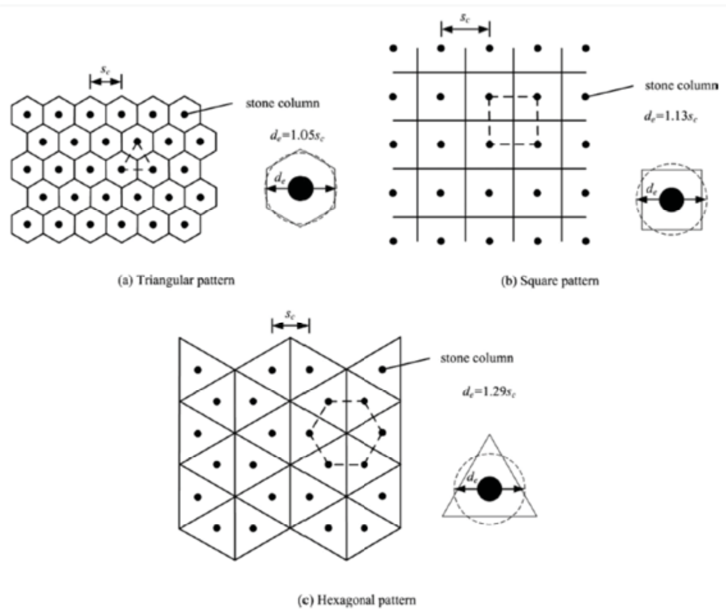
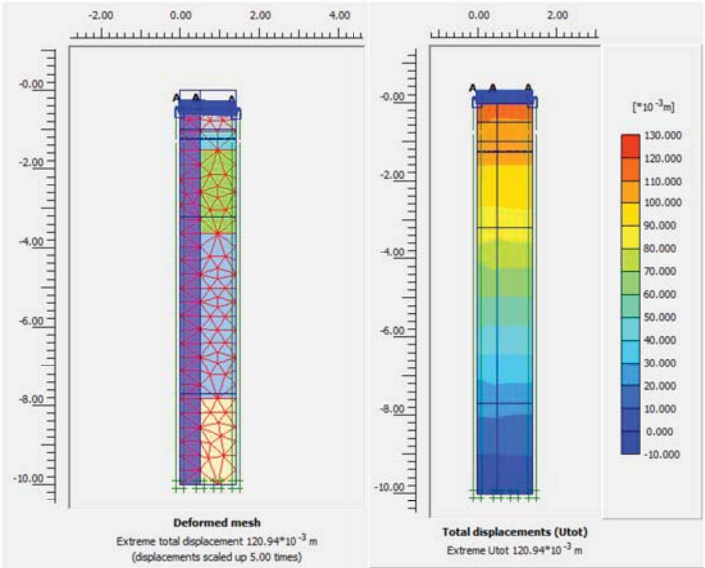


Figure 3. Typical Stone Columns Arrangement Patterns with the Equivalent Diameters (Wang 2009).



(a) (b)

Figure 4. (a) Deformed mesh and (b) Total Displacements of the end bearing stone column.

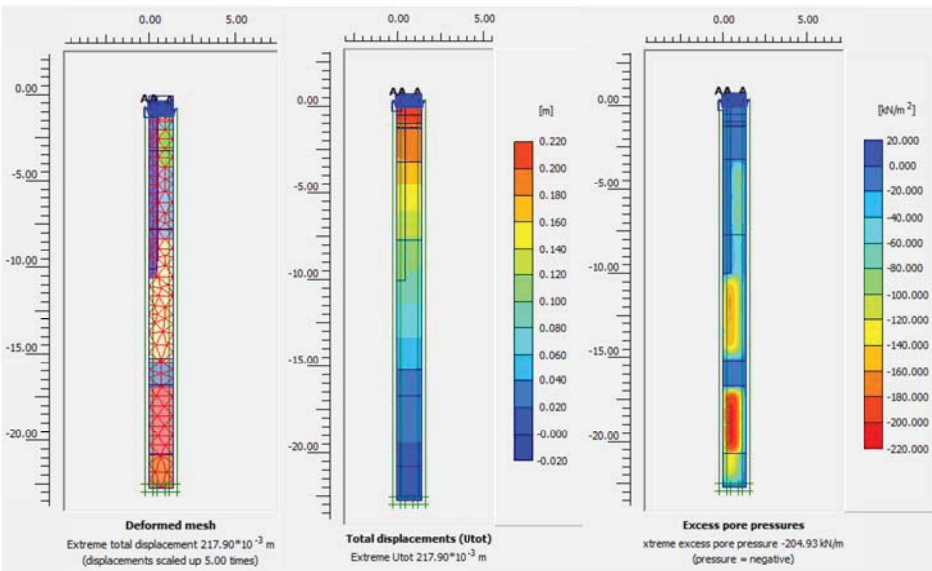
Figure 5(a) shows the deformed mesh of a unit cell column modelunder 225 kPa of foundation pressure. Furthermore, Figure 5(b) shows the total displacementsof the stone column,where the shadings get darker as the displacement decreases. This indicates that lower region of the model is experiencing lesser displacement as compared to the upper region and the settlement is decreasing as the depth increases.The results obtained from numerical model and theoretical method are compared and analysed.

When the surcharge is increased to 225 kPa, the theoretical method showsthe total displacements of 126.1 mm whereas the numerical result is approximately 218 mm as shown in Figure 5(b). The discrepancy occurred as a result ofPriebe's method which is mainlyusedto designend-bearing stone columns where the consolidation settlements below the toe were not considered in the theoretical calculation.

On the other hand, finite element analysis can consider the dissipation of excess pore water pressures which will cause more settlements as the excess pore water pressure gets dissipated. However, this was not considered in Priebe'smethod. It can be seen that the excess pore water pressure built-up below the column tip has increased to 160 kPa under loading condition as shown in Figure 5(c).

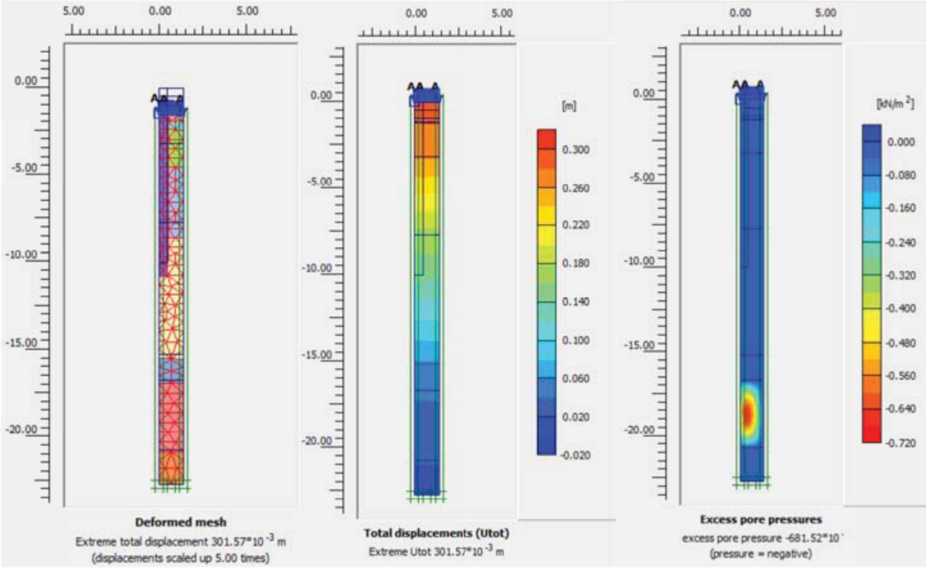
However, the criteria for post-construction settlements of the stone column shall not exceed the limit of 250 mm upon completion of the project. An additional settlement of 84 mm is recorded after dissipation of excess pore water pressures under constant loading of 225 kPa as shown in Figure 6(b).

It is observed in Figure 5(c) that the excess pore water pressures built-up under the toe of stone column has increased to 160 kPa due to incremental loading. The stone columns technique form a composite foundation supporting system and also acts as vertical drains which resulted in rapid consolidation due to dissipation of excess pore water pressures in soft soils. Notably, in a total of 37 days as generated by finite element analysis, all excess pore water pressures would have been fully dissipated in the soft soil layers as shown in Figure 6(c). All the excess pore water pressures around and below the stone column would have been fully dissipated within a month. It can be concluded that finite element software has taken into account the time-dependent dissipation of excess pore pressures. Therefore, it is more suitable and reliable to use finite element method in designing floating stone column than Priebe'sempirical method.



(a) (b) (c)

Figure 5. (a) Deformed mesh of column; (b) Total displacement of column; (c) Excess Pore Water Pressures built-up around and under the floating stone column when 225 kPaload was applied.



(a) (b) (c)

Figure 6. (a) Deformed mesh of column; (b) Total displacement of column; (c) Excess Pore Water Pressures dissipated when 225 kPaload was applied.

Table 5.Comparison between Theoretical Calculation & Finite Element Analysis.

Method Used	Theoretical Calculation	Finite Element Analysis- Axisymmetric Model	
	Priebe – End-bearing Stone Column	End-bearing Stone Column	Floating Stone Column
Immediate Settlement of the Composite System (mm)	**126.13**	**120.94**	**217.90**

Table 5 summarises the theoretical and finite element analysis results. By comparing Priebe's result with the finite element result, the settlement of the stone column in the theoretical calculation is differed by approximately 5 mmwhich is comparable with the finite element result. However, the immediate settlement of the floating stone column is approximately twofold increase of the Priebe's method as the dissipation of excess pore water pressures below the toe of stone column is not considered in Priebe's method.Besides, the finite element analysis has taken into account the built-up of excess pore water pressures below the toe of floating stone column where the soil layers were not treated. From the analyses carried out herein, it is acknowledged that the more important and sensitive parameter is the value of the Young's modulus selected for the stone column and the surrounding soils, rather than their corresponding strength parameters.

On the other hand, the immediate and consolidation settlements of the untreated soil layers below the stone column tip are required to be taken into account as the consolidation of soft soil will cause more settlements.Furthermore, Priebe's method did not consider the post-construction settlements of the stone column and the untreated soil layers below the toe of floating stone column. Hence, the settlement recorded forthe floating stone columnvaried around twice the value of calculated end-bearing stone column as the Priebe's method was mainly developed to design end-bearing stone columnsas in this case study (Bouassida et al. 2009).

6. CONCLUSION

This paper mainly focused on the design of stone column that provides total settlements inan infinite loaded area. Based on theoretical calculations, it was observed that the stone column significantly reduces settlement at the treated layers. The end-bearing stone column was first validated through Priebe's method which provides good agreement with numerical results. The results of stone column installed on rigid layer obtained from both methods indicate that finite element model has the ability to provide a promising and equivalent result by reproducing the behaviour of stone column under loadings.Subsequently, the floating stone column is modelled using finite element model to understand the behaviour of the floating stone column under loadings.

In this study, axisymmetricfinite element analysis was adopted to simulate a unit cell stone column under a loading pressure of 225 kPaexerted on an infinite loaded area to determine the total settlement of the composite system. Back-analysis has been performed using axisymmetric model to study the settlements of the floating stone column installed in soft soils. However, the total displacements obtained from the numerical results of a unit cell stone column aretwo times more than theoretical calculations developed by Priebe as it is mainly developed to design end-bearingstone columns and the consolidation settlement of the soft soils was not considered as well. Hence, this shows that Priebe'stheory is inappropriatefor designing floating stone column as compared tothe finite element analysis that considersconsolidation of soft soil and dissipation of excess pore water pressure at the toe of the stone column.

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REFERENCES

Afshar, J. N., and Ghazavi, M. (2014). "Experimental Studies on Bearing Capacity of Geosynthetic Reinforced Stone Columns." *Arabian Journal for Science and Engineering*, 39(3), 1559-1571.

Alonso, J., and Jimenez, R. (2011). "Reliability Analysis of Stone Columns for Ground Improvement." *Geo-Risk 2011*, 493-500.

Ashmawy, A., Rokicki, R., and Plaskett, M. (2000). "Predicted and Actual Settlement of Soils Improved by Vibro Replacement." *Advances in Grouting and Ground Modification*, 281-295.

Balaam, N. P., and Booker, J. R. (1981). "Analysis of rigid rafts supported by granular piles " *International Journal for Numerical and Analytical Methods in Geomechanics*, 5(4), 379-403.

Black, J. A., Sivakumar, V., Madhav, M. R., and Hamill, G. A. (2007). "Reinforced Stone Columns in Weak Deposits: Laboratory Model Study." *Journal of Geotechnical and Geoenvironmental Engineering*, 133(9), 1154-1161.

Bolton, M. D. (1986). "The Strength and dilatancy of sands." *Geotechnique*, 1, 65 - 78.

Bouassida, M., Ellouze, S., and Hazzar, L. (2009). "Investigating Priebe's method for settlement estimation of foundation resting on soil reinforced by stone columns." *Geotechnics of Soft Soils: Focus on Ground Improvement*, 321-325.

Cimentada, A., and Costa, A. D. (2008). "Laboratory experimental analysis of radial consolidation around a stone column." *Geotechnics of Soft Soils: Focus on Ground Improvement*, 213 -217.

Frikha, W., Bouassida, M., and Canou, J. (2014). "Parametric Study of a Clayey Specimen Reinforced by a Granular Column." *International Journal of Geomechanics*, 04014078.

Han, J., and Ye, S. (2001). "Simplified Method for Consolidation Rate of Stone Column Reinforced Foundations." *Journal of Geotechnical and Geoenvironmental Engineering*, 127(7), 597-603.

Han, J., and Ye, S. (2002). "A Theoretical Solution for Consolidation Rates of Stone Column - Reinforced Foundations Accounting for Smear and Well Resistance Effects." *International Journal of Geomechanics*, 2(2), 135-151.

Kirsch, F. (2006). "Vibro Stone Column Installation and its Effect on Ground Improvement " *Proceedings of the International Conference on Numerical Modelling of Construction Processes in Geotechnical Engineering for Urban Environment*, Taylor and Francis, Bochum, Germany, 115– 124.

Munfakh, G. A., Sarkar, S. K., and Castelli, R. J. (1983). "Performance of test embankment founded on stone columns." *Proc. Int. Conf. on Adv. in Piling and Ground Treatment for Found*, 259-265.

Ng, K. S., and Tan, S. A. (2014). "Design and analyses of floating stone columns." *Soils and Foundations*, 54(3), 478-487.

Priebe, H. J. (1995). "The design of vibro-replacement." Keller Grundbau GmbH.

Raju, V. R., Krishna, R. H., and Wegner, R. (n.d.). "Ground Improvement using Vibro Replacement in ASIA 1994 to 2004 - A 10 Year Review." Keller (M) Sdn. Bhd., Malaysia.

Shao, L., and Gularte, F. (2007). "Instrumentation for Vibro Stone Column Soil Improvement." *7th FMGM 2007*, 1-12.

Sim, Y. S., Ong, D. E. L., Leung, C. F., and Yee, Y. W. (2015). "Performance Of "Floating" Stone Columns Installed In Thick, Soft Soils." *International Conference on Soft Ground Engineering (ICSGE 2015).* Singapore.

Tan, S. A., Ng, K. S., and Sun, J. (2014). "Column Groups Analyses for Stone Column Reinforced Foundation." *Proc., Geo-Congress 2014*, 597-608.

Wang, G. (2009). "Consolidation of Soft Clay Foundations Reinforced by Stone Columns under Time-Dependent Loadings." *Journal of Geotechnical and Geoenvironmental Engineering*, 135(12), 1922-1931.

Zahmatkesh, A., and Choobbasti, A. J. (2010). "Investigation of Bearing Capacity and Settlement of Strip Footing on Clay Reinforced with Stone Columns." *Australian Journal of Basic and Applied Sciences*, 4(8), 3658-3668.