

# SETTLEMENT RATIO OF FLOATING STONE COLUMNS FOR SMALL AND LARGE LOADED AREAS

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## ABSTRACT

This paper presents two set of 2D finite element analyses that study on the settlement ratio of floating stone column for small and large column groups. The settlements of floating stone columns are difficult to be predicted especially for large column groups. Unit cell model was used in this study for large column group assuming infinite column grid. The influence of key parameters such as column length, area replacement ratio, loading intensity and post installation lateral earth pressure on the settlement ratio were investigated. Based on the results, a simplified solution was proposed to calculate the settlement ratio for floating stone columns. On the other hand, the settlement performance of floating stone column in small group was examined for different area replacement ratio and column length. Design chart developed from this study was validated by a case study where a reasonable agreement was obtained.

*Key words:* Floating stone columns, settlement ratio, unit cell, finite element.

## 1. INTRODUCTION

Stone column is a proven technology in improving the soft ground for many geotechnical applications such as road embankment, airfield, residential and light commercial and industrial structures. Stone columns are normally constructed to penetrate soft soil layer and founded on more competent soil layer. This is termed as fully penetrating columns or end bearing columns. Nonetheless, partially penetrating columns or floating columns with toe embedded within soft clay layer are sometimes used. Most of the time, stone columns are used in groups, either under the large loaded area or small loaded area. Understanding the differences in failure mechanisms of the large and small column groups are vital in estimating the performance of stone columns.

The complex interactions of column-foundation-surrounding soil influence the load settlement behavior and the failure mechanism of the stone column improved ground. As the size of stone column groups increase, the spreading of vertical stress decreases and the stress transfer resembles that of a unit cell (Barksdale and Bachus 1983). Most of the design methods for calculating drained settlements for large column groups are developed based on the unit cell model (e.g., Balaam and Booker 1981; Priebe 1995; Ng and Tan 2015). Large number of field data is available for large column groups (McCabe *et al.* 2009). However, almost all of them reported on the stone columns of end bearing type. Very limited information is available on the settlement performance of floating stone columns for large column groups. Hence, it will be useful for the practical engineers if the performance of floating stone columns can be predicted from the results of end bearing columns.

There is no distinct definition for small and large column groups. However, it should be related to the width of foundation and the thickness of layer needing improvement. It is suggested if the width of foundation is more than 2 times the soft soil thickness, the stone columns can be regarded as large column groups, or otherwise. For large column groups, the settlement of innermost column can be simulated using unit cell concept by considering infinite grid condition. On the other hand, the settlement prediction for small column groups is more complicated than large column groups because of the stress attenuation with the soil mass over the depth and it is also due to the lesser degree of confining effect. Most of the design procedure deals with elastic approach (e.g., Rao and Ranjan 1985; Lawton and Fox 1994; Sehn and Blackburn 2008) do not incorporate the idea of optimum length (Tan *et al.* 2014). Wood *et al.* (2000) discussed the idea of optimum length invoked from the small scale model test where in small column groups the depth at which the prevalent strains are found is primarily controlled by the diameter of the footing itself, and somewhat influenced by the area ratio. Until today, there is no study to investigate the settlement behavior of small group floating stone columns using the results of large end bearing stone column groups. This study tried to fill the gap of knowledge.

This paper reports on the settlement performance of floating stone columns for small and large column groups by means of finite element (FE) study. The FE results are presented in terms of settlement ratio ( $S/S_{uc}$ , where  $S$  is the settlement of floating column group and  $S_{uc}$  is the settlement of end bearing column in the unit cell model). In other words, the performance of floating stone columns either for large or small groups can be predicted using the results of large group end bearing type columns. So far, the literature review has shown the convenient of reporting the beneficial of column inclusion in soft ground using settlement improvement factor,  $n$  (ratio of settlement of untreated ground over settlement of treated ground) or settlement reduction ratio,  $1/n$  in almost all stone columns studies or case histories. With the introduction of this settlement ratio, it would be of great practical

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use if the floating stone columns are to be designed since the performance of end bearing columns for large stone column group can be readily predicted by many available methods such as the most popular method by Priebe (1995). The author’s earlier works based on the same study (Ng and Tan 2014) has proposed a simple method to obtain the settlement improvement factor for the end bearing columns under infinite grid condition, valid for  $\alpha = 0.1 \sim 0.45$  as shown in Eq. (1).

$$n = 9.43\alpha^2 + 1.49\alpha + 1.06 \tag{1}$$

where  $\alpha$  (area replacement ratio) is the ratio of stone column area over the area of treated soil.

## 2. LARGE COLUMN GROUPS

### 2.1 Numerical Model

In this study, a large group of stone columns was modeled adopting unit cell idealization in FE analysis using the geotechnical program PLAXIS 2D. The analyses utilized the Tan *et al.* (2008) model as reference case where a unit cell was modeled as axial- symmetry with instantaneous vertical loading of 100 kPa uniformly applied through a rigid plate overlying a 10.0 m fully penetrating stone column (*i.e.*, depth ratio  $\beta = L/H = 1.0$ ;  $L =$  length of column,  $H =$  thickness of soft soil) as shown in Fig. 1. The unit cell model utilized an area replacement ratio,  $\alpha$  of 0.11 with column diameter of 0.85 m and influence radius,  $r_c$  of 1.275 m. The standard boundary conditions in the model were assumed such that the vertical boundaries are free vertically and constrained horizontally while the bottom horizontal boundary is fully fixed. Full saturation condition was assumed in the study and drained analyses were performed for all the cases analyzed. Both stone column and soft soil were modeled as elastic-perfectly plastic model *i.e.*, Mohr-Coulomb (MC) model. Material properties are shown in Table 1. The strength parameters for soft soil and columns materials (friction angle,  $\phi'$  and cohesion,  $c'$ ) are typically adopted design values. The modular ratio,  $m = E_c / E_s$  was taken as 10 which is in the typical range of 10-20 according to Barksale and Bachus (1983) for soft soil, where  $E_c$  is the Young’s modulus of column material and  $E_s$  is the Young’s modulus of surrounding soil. Initial stresses were generated with  $K_o$  procedure with the proposed value of lateral earth pressure,  $K_o = 0.7$  for both column and soil reflecting wish-in-place approach adopted in the model.

A parametric study was conducted to examine the influence of key parameters on the settlement ratio of floating stone columns. The key parameters include area replacement ratio, friction angle of column material, loading intensity and post installation lateral earth pressure. The details of this series of tests are tabulated in Table 2. One parameter was altered from the reference case each time to investigate the influence of each parameter on the settlement performance. The results and discussion are shown in the following sections. Comparison can be made to Ng and Tan (2014) where the numerical results are presented in terms of settlement improvement factor. Current study has also highlighted on the changes in stress concentration ratio,  $n_s$  (ratio of stress acting on the column to the surrounding soil) when the key parameters varied.

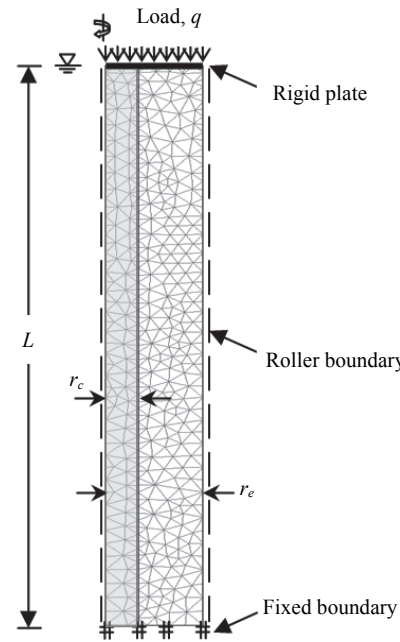


Fig. 1 Baseline case Tan *et al.* (2008) model

Table 1 Materials properties for the unit cell models

ID	Name	Type	$\gamma_{sat}$ (kN/m <sup>3</sup> )	$\nu'$	$E'$ (kN/m <sup>2</sup> )	$c'$ (kN/m <sup>2</sup> )	$\phi'$ (°)
1	Soft soil	Undrained	15	0.3	3,000	0.1	22
2	Stone column	Drained	15	0.3	30,000	1	40

Table 2 Test series for parametric study

Influence factor	Range of value
$\alpha$	0.11*, 0.15, 0.2, 0.25, 0.35, 0.45
$\phi_c'$ (°)	40*, 45, 50, 55
$q$ (kPa)	50, 100*, 150, 200, 250
$K_0$	0.7*, 1.0, 1.5

\* indicates the parameter for the reference case

### 2.2 Influence of Area Replacement Ratio

The settlement of untreated ground with similar loading condition as in the reference case is 248 mm. Figure 2 shows the results on the settlement of floating stone column in the unit cell for different area replacement ratios. As the depth ratio of stone column increases (fully penetrating if  $\beta = 1$ ), the settlement reduces. This result proves the potential of floating stone columns in reducing the compressibility of soft soil by providing higher composite stiffness for the improved layer. If 125 mm of settlement is to be achieved, the necessary replacement ratio ( $\alpha$ ) for the end bearing column is 0.25. For the floating column with  $\beta$  of 0.7, it is  $\alpha = 0.45$ .

Similar to the performance of end bearing columns, floating stone columns demonstrate improved performance when the area replacement ratio,  $\alpha$  increases. The increase is the result of higher

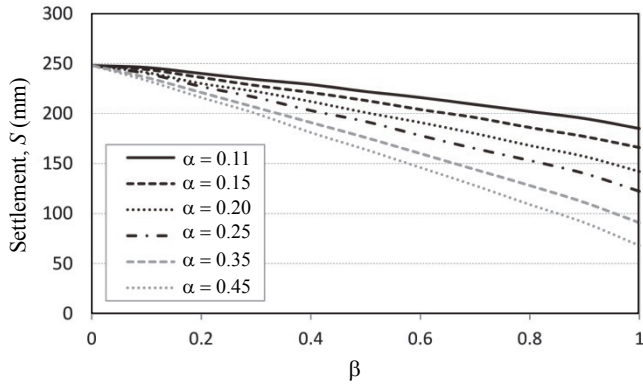


Fig. 2 Settlement of floating stone column in unit cell

composite stiffness attained when more number of columns per unit area are installed in the ground. Besides, as the area replacement ratio increases, more stresses are concentrated on the column compared to the surrounding soil (Fig. 3). The stress concentration ratio,  $n_s$  (ratio of stress acting on the column to the surrounding soil) increases from 4 to 5, obtained for depth 0.1 m below ground surface. These values fall within the typical range (*i.e.*,  $n_s = 3 \sim 6$ ) measured at site. End bearing columns and floating columns yielded the same results. The stress concentration ratio reduced from 5 to 2.4 (at  $\alpha = 0.45$ ) as the depth goes deeper. The reduction of stress concentration ratio with depth was also reported by Lee (2000) and Hong (2003). However, at depth 5.0 m below ground surface, the stress concentration ratio remains constant as area replacement ratio increases. The result can be represented by Eq. (2) which relate the area replacement ratio to the stress concentration ratio at the column's head.

$$n_s = 3.1\alpha + 3.6 \tag{2}$$

The settlement ratio of large group floating stone column is presented in Fig. 4. The settlement ratio reduces as the column length increases until unity (end bearing condition where  $\beta = 1.0$ ). Higher area replacement ratio results in a higher settlement ratio. For instance, at  $\beta = 0.1$ , the settlement ratio is near to 3.5 which means about 3.5 times the settlement of floating stone column compared to the end bearing columns. A near-linear relationship of settlement ratio with area replacement ratio and depth ratio can be represented by Eq. (3). Area replacement ratio is the most important variable in floating stone columns design other than the length of columns. By careful selection of these two variables, a design engineer can provide optimum design for the stone column improved ground.

$$\frac{S}{S_{uc}} = 1 + 7.9\alpha^{1.4}(1-\beta) \tag{3}$$

**2.3 Influence of Friction Angle of Column Material**

Figure 5 depicts the effect of different friction angles of column material on the settlement ratio. The settlement ratio reduces when the friction angle of column reduces. It is known that higher friction angle deters the occurrence of plastic points due to material yielding at low strain by increasing the yield limit of the column material. The effect reduces for low  $\beta$  value because the failure mechanism change from shearing in the column to

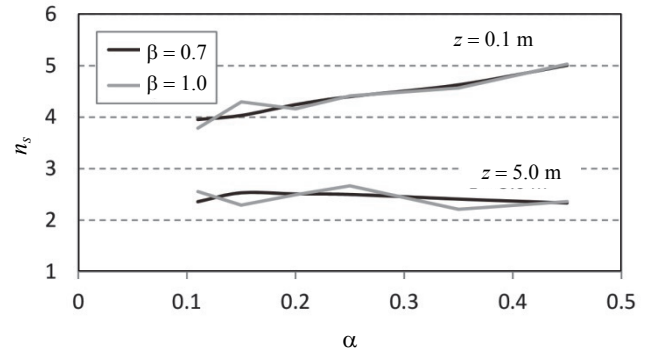


Fig. 3 Stress concentration ratio for different area replacement ratio

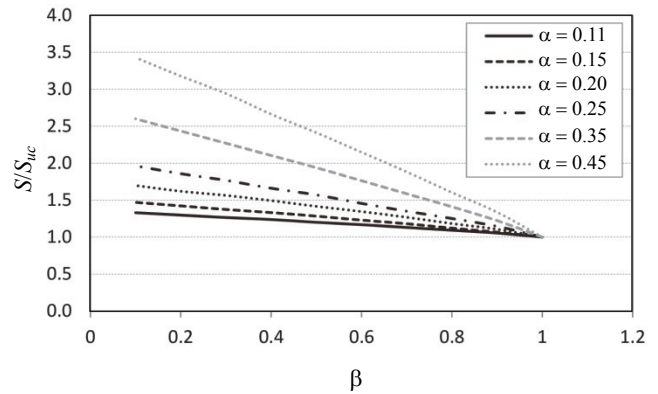


Fig. 4 Influence of area replacement ratio on settlement ratio

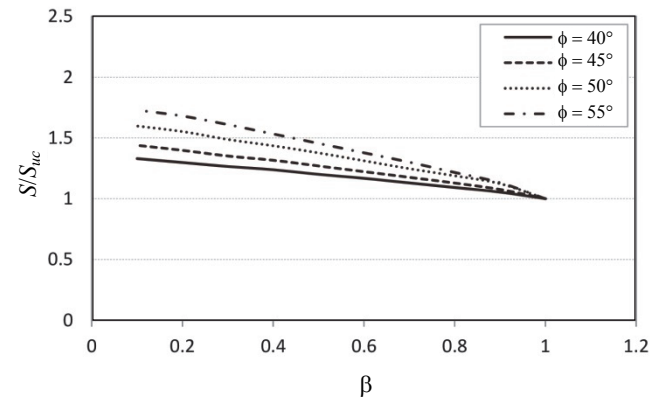


Fig. 5 Influence of friction angle of stone column material on settlement ratio

punching. In a few studies, laboratory shear box test produces high friction angle ( $\phi_c' \geq 50^\circ$ ) for stone column material (Herle *et al.* 2008). However, it is difficult to achieve high friction angle (or high degree of compaction) during actual stone column installation especially when the surrounding soils are very weak (low confining strength). From this study, the relationship of settlement ratio with friction angle and depth ratio can be presented by Eq. (4).

$$\frac{S}{S_{uc}} = 1 + [0.029(\phi - 40^\circ) + 0.38](1-\beta) \tag{4}$$

The settlement ratio can be predicted using Eq. (5) by combining the effect of area replacement ratio and column's friction angle:

$$\frac{S}{S_{uc}} = 1 + [7.9\alpha^{1.4} + 0.029(\phi - 40^\circ)](1 - \beta) \quad (5)$$

Stress concentration ratio,  $n_s$  is much affected when the friction angle of the column material changes. For example, floating column with  $\beta = 0.7$  and  $\phi'_c = 50^\circ$  has stress concentration ratio,  $n_s$  of 6.5 near the surface while  $n_s = 3.5$  at depth of  $z = 5$  m. The increase of stress concentration ratio with the increase of the column friction angle is well demonstrated in Fig. 6. Identical results are obtained for floating columns and end bearing columns. Higher shear strength of column material prevent earlier yielding of column, and enable columns to attract more loads. In addition, less load transfer to surrounding soil simply means less induced settlement for the whole improved system. The stress concentration ratio can be predicted using Eq. (6).

$$n_s = 0.0012\phi_c'^{2.2} \quad (6)$$

The combined effect of area replacement ratio and column's friction angle on the stress concentration ratio is computed as follows:

$$n_s = 3.1\alpha - 0.4 + 0.0012\phi_c'^{2.2} \quad (7)$$

### 2.4 Influence of Loading Intensity

The influence of the applied loading on the settlement ratio of floating stone columns is depicted in Fig. 7. As the load increases, the settlement ratio reduces. However, the difference is small especially for  $q$  beyond 100 kPa. This reduction is mainly due to plastic straining of the column and soil. As load increases, more plastic points are developed around the soil near the column. In other words, there is little gain in shear strength for the improved ground while the loading keeps increasing. The column length has not much effects on the settlement ratio.

The effect of applied loading on the stress concentration ratio,  $n_s$ , was examined as well. It was found that the increase of  $n_s$  with the increase of loading intensity is negligible ( $n_s \approx 3.9$  to 4 for  $q = 50$  to 400 kPa). Ichmoto (1981) and Kim (2001) drew the same conclusions while other researchers like Watts *et al.* (2000) reported the increase of the stress concentration ratio due to the increase of loading intensity obtained from field load test results while Greenwood (1991) load test result showed significant reduction of stress concentration ratio as the applied load increased.

### 2.5 Influence of Post Installation Lateral Earth Pressure

To account for the installation effect, the post installation lateral earth pressure,  $K$  was utilized. Based on the back analysis for a full scale load test, Elkasabgy (2005) showed the values of  $K$  fell between 0.7 and 2.0 with average of 1.2. In the current study, the influence of this parameter on settlement ratio is shown in Fig. 8. Higher  $K$  value results in higher settlement ratio but the effect is negligible. Similar to other key variables, the effect dismisses as  $\beta$  increases. Again, the study here shows the stress concentration factor is not much affected by the variation in  $K$  value ( $n_s \approx 4.0$  for  $K = 0.7, 1.0$  and 1.5).

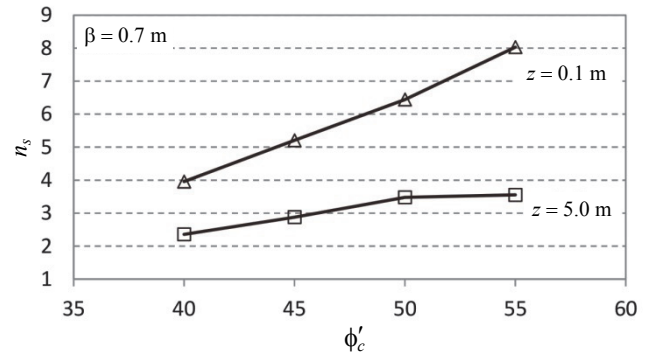


Fig. 6 Influence of column's friction angle on stress concentration ratio

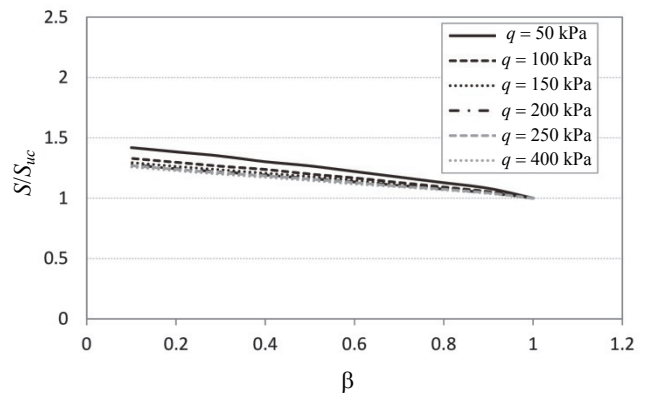


Fig. 7 Influence of loading intensity on settlement ratio

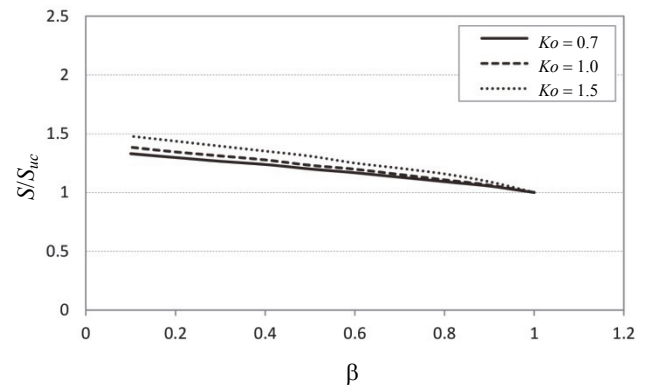


Fig. 8 The influence of post installation lateral earth pressure on settlement ratio

### 2.6 Comparison of Settlement Ratio Prediction with Other Methods

The prediction model using Eq. (5) was compared with three different methods, namely Aboshi *et al.* (1979); Priebe (1995); Chai and Pongsivasathit (2010). All these methods require the settlement to be calculated for both improved and unimproved layer. The settlement of unimproved layer was calculated using the constraint modulus of soil,  $E_{s, oed}$ .

In Aboshi's method adopting vertical equilibrium concept, the stresses in the soil,  $\sigma_c$  is calculated as:

$$\sigma_c = \frac{\sigma}{[1 + (n_s - 1)\alpha]} \quad (8)$$

where  $\sigma$  if the applied vertical stress. The stress concentration ratio,  $n_s$  in the above equation can be predicted using Eq. (1). Assuming fully penetrating condition, the settlement of improved layer can be computed using one dimensional settlement approach,  $S_{uc} = \sigma_c L / E_{s,oad}$ . Priebe (1995) proposed the settlement improvement factor,  $n_2$  to calculate the settlement for the end bearing columns. On the other hand, Chai and Pongsivasathit (2010) proposed the settlement calculation procedure for floating cement columns based on a finite element analysis.

The comparison results in terms of the settlement ratio for  $\alpha = 0.2$  and  $0.35$  are shown in Figs. 9 and 10, respectively. Identical results are obtained for Eq. (5) with FEM since the simplified solution is based on the current FEM analysis. Aboshi's method compared quite well to the prediction model albeit slightly under prediction when  $\alpha$  and  $\beta$  are small. The good prediction of Aboshi's method is because of right stress concentration value being chosen. Both Priebe (1995) and Chai and Pongsivasathit (2010) predicted higher  $S/S_{uc}$ . In other words, these two models overestimated the settlement for floating stone columns. However, the magnitude of overestimation reduced when  $\alpha$  gets larger. Overestimation of Priebe's method is probably due to the fact that this method is customized for end bearing condition where punching behavior of floating columns are not considered. For Chai and Pongsivasathit's method, it is developed for cement column with high stiffness and characterized using elastic model, therefore the yielding of stone columns cannot be captured.

### 3. SMALL COLUMN GROUPS

#### 3.1 Numerical Model

Unlike most of infinite column group, small column groups are normally constructed to "float" where column's toe does not reach the competent layer. Wood *et al.* (2000) described that column length is relevant only up to a certain point, beyond that point, increasing the length of the columns,  $L$  confers no further advantage. This study investigated the influence of column length over the settlement performance and intended to search the optimum length,  $L_{opt}$ . Spread footings supported by a group of columns (*i.e.*, 4, 9, 16, 25, 36, 49, 64, 81 and 100 columns) were investigated using FEM 2D axisymmetrical models. Concentric ring model proposed by Elshazly *et al.* (2008) was used to convert the off center columns to the equivalent cylindrical rings. This 2D simplification has been validated in Tan *et al.* (2013) where good agreement was obtained compared to 3D model. Figure 11 shows the numerical model for 9 column group. A uniform load,  $q = 100$  kPa was applied over a rigid footing of diameter,  $D$  overlying on a granular bed of 0.5 m thick. All columns studied are of the floating type with diameter,  $d_c$  of 1.0 m. Boundary effect was studied where horizontal boundary has to be at least 3 times the footing diameter away while vertical boundary has to be 4 times deeper than the footing diameter. Material properties are presented in Table 3. More details on the numerical models can be referred to Tan *et al.* (2014).

#### 3.2 Numerical Results and Discussion

Physical observations from the numerical study explained that the settlement performance of a column group is a combined effects of few complex mechanisms (shear, bending, and punching failure modes) corresponding to the load applied associated

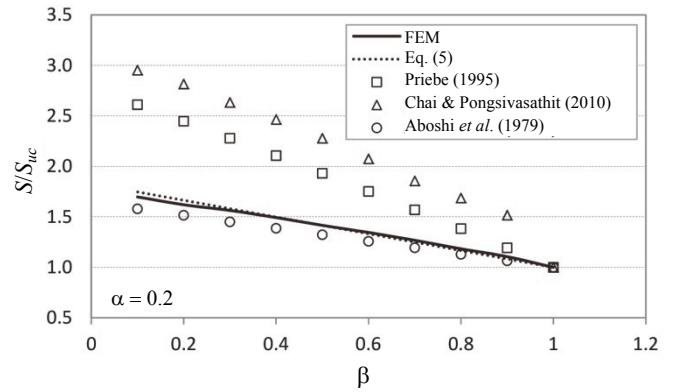


Fig. 9 Comparison results for settlement ratio at  $\alpha = 0.2$

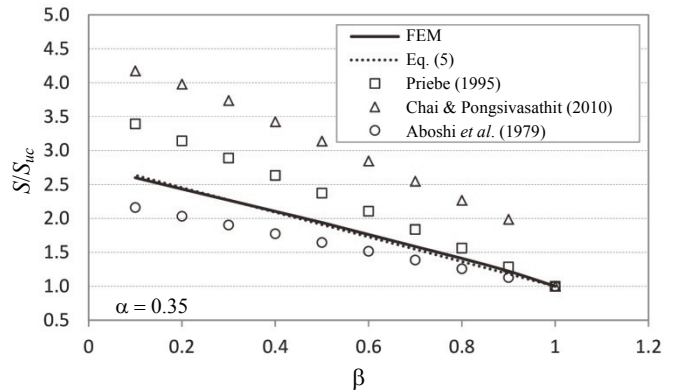
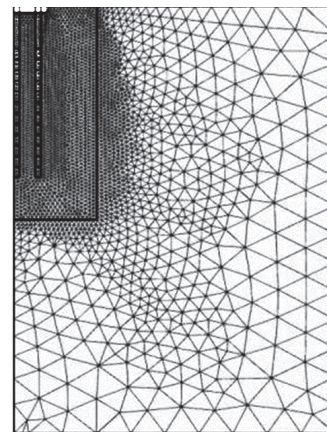


Fig. 10 Comparison results for settlement ratio at  $\alpha = 0.35$



General information  
 Model: Axisymmetry  
 Elements 15-Noded  
 Nr of soil elements: 5291  
 Nr of nodes: 42695  
 Average elem. size: 0.4546 m  
 Boundary > 4B

Fig. 11 Numerical model of small column groups

Table 3 Materials properties for column group

Name	Soft soil	Stone column	Granular bed
$\gamma_b$ or $\gamma_{sat}$ (kN/m <sup>3</sup> )	18	18	18
$\nu'$	0.3	0.3	0.3
$E'$ (kPa)	3000	30000	10000
$c'$ (kPa)	0.1	0.1	0.1
$\phi'$ (°)	25	40	30
$K_o$	0.7	0.7	0.7

with other fundamental aspects like overall stability and stiffness (Tan *et al.* 2014). Key finding is that the size of the footing interacts with the individual columns to produce a global mechanism of deformation in the columns system. This study has shown that for all the cases analyzed, the  $L_{opt} / D$  values are ranging from 1.20 to 2.2 for low to high area replacement ratios as presented in Table 4. For the same number of columns, higher area replacement ratio means a smaller diameter of footing and a closer spacing of columns. Greater optimum length for higher area replacement ratio in fact explains the ability of longer columns to transfer the stress from the top to a depth further below. Castro (2014) recommended the optimum length as two times the breath of footing.

The settlement ratio,  $S / S_{uc}$ , relates the settlement of small group floating columns with the end bearing columns of infinite column grid. This study examines column up to 32 m even though the length of 40 m using wet construction method has been constructed and it is quite common to see soft soil with thickness more than 40 m. The range of number of columns examined is between 4 to 100. The settlement ratios of floating stone columns of  $\alpha = 0.2, 0.4$  and  $0.6$  are shown in Figs. 12 to 14. The settlement of end bearing column in unit cell model,  $S_{uc}$  was calculated based on the thickness of improved depth,  $H$  (where  $H$  is equal to column length,  $L$ ) with  $E_{s, oed} = 4,038 \text{ kN/m}^2$  using Eq. (1). The settlement ratio increases with the increasing number of columns or area replacement ratio. Generally,  $S / S_{uc}$  is larger than unity due to the dominant punching behavior in the short columns and the relatively closer spacing causing the block failure effect. When the number of columns and area replacement ratio are small, the settlement ratio can be less than unity. Besides, lateral spreading of soil below footing also contribute to more settlements. As the column length exceeds the optimum length, no additional settlement is observed in floating stone columns, but in the unit cell model, the settlement increases as the thickness of treatment increases, thus leading to the slight reduction in  $S / S_{uc}$ . Figures 12 to 14 can be used as design charts for practical engineer to predict the settlement of floating stone columns. The influence of loading intensity has not been studied. However, the effect of plastic straining in the improved layer for floating columns is assumed to be similar to the end bearing columns and hence they compensate each other. The design example is given as below:

**Design example:** A group of 9 stone columns with area replacement ratio,  $\alpha$ , of 0.2, loading intensity,  $q$ , of 100 kPa, and length,  $L$ , of 10 m is to be installed in a thick soft ground with constraint modulus of  $E_{s, oed}$  of 4,038 kPa. The settlement of this floating stone column group is calculated as follows.

**Step 1:** Calculate the settlement of untreated ground under oedometric condition,  $S_{s, oed}$

$$S_{s, oed} = qL / E_{s, oed} = 100 / 4038 \times 10 = 0.248 \text{ m}$$

**Step 2:** Use Eq. (1) to predict the settlement improvement factors of end bearing columns in unit cell condition.

$$n = 9.43(0.2)^2 + 1.49(0.2) + 1.06 = 1.735$$

**Step 3:** Calculate the settlement of end bearing columns in unit cell condition,  $S_{uc}$

$$S_{uc} = S_{s, oed} / n = 0.248 / 1.735 = 0.143 \text{ m}$$

**Step 4:** Obtain  $S / S_{uc}$  from Fig. 12 with  $\alpha = 0.2$  and  $L = 10 \text{ m}$   
 $S / S_{uc} \approx 1.2$

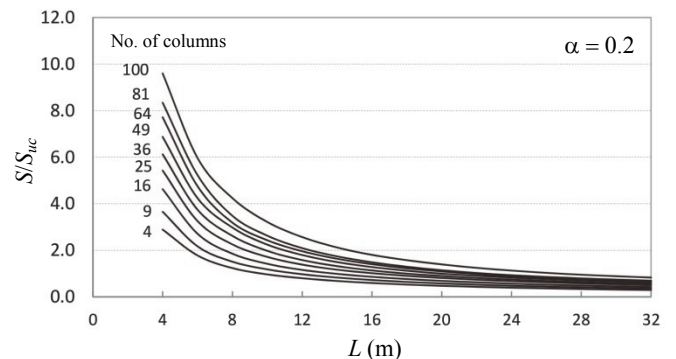
**Step 5:** Compute the settlement,  $S$  of floating column groups.

$$S = S / S_{uc} \times S_{uc} = 1.2 \times 0.143 = 0.17 \text{ m}$$

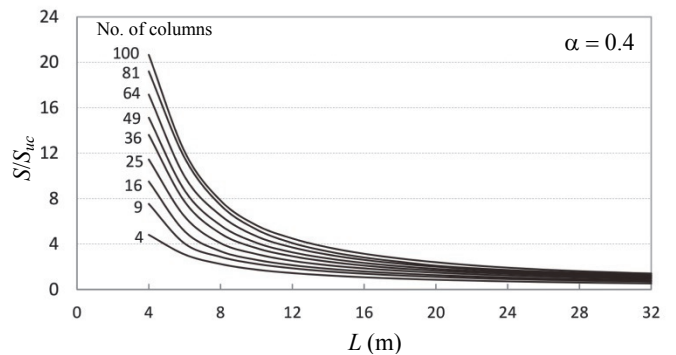
Therefore, the settlement of 9 floating column groups is estimated to be 0.17 m.

**Table 4 Optimum length for small column groups**

No. of columns	$\alpha$	$D$ (m)	$L_{opt}$ (m)	$L_{opt} / D$
4	0.2	4.47	8	1.79
	0.7	2.39	5	2.09
9	0.2	6.71	10	1.49
	0.7	3.60	8	2.22
16	0.2	8.94	12	1.34
	0.7	4.78	10	2.09
25	0.2	11.18	14	1.25
	0.7	6.00	12	2.00
36	0.2	13.42	16	1.19
	0.7	7.17	16	2.23
49	0.2	15.65	18	1.15
	0.7	8.37	18	2.15
64	0.2	17.89	22	1.23
	0.7	9.56	20	2.09
81	0.2	20.13	24	1.19
	0.7	10.76	22	2.04
100	0.2	22.36	28	1.25
	0.7	11.95	26	2.18



**Fig. 12 Settlement ratio of  $\alpha = 0.2$  for small column groups**



**Fig. 13 Settlement ratio of  $\alpha = 0.4$  for small column groups**

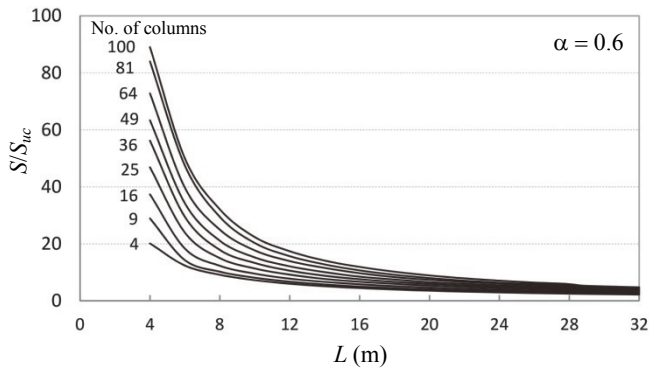


Fig. 14 Settlement ratio of  $\alpha = 0.6$  for small column groups

Priebe (1995) presented a design chart relating the settlement ratio of spread footing for the end bearing column considering the stress distribution below the footing and the lateral confinement effect. No details on the area of footing and area replacement ratio are provided. It is known that the increase in the area replacement ratio reduces the settlement for small and infinite column grid. The author claimed that the settlement of small column groups and the settlement of infinite column grid compensated each others for stone columns with  $\alpha > 0.1$ . There was no discussion on the optimum length made by Priebe (1995). The current study focuses on the floating column type and therefore no direct comparison can be made with Priebe’s results. However, for reference purpose, the results of  $\alpha = 0.2$  in this study was plotted together with Priebe (1995) as shown in Fig. 15. Non dimensional form is used for the length of column, denoted as depth ratio,  $\lambda = L/d_c$ . However, current study has shown the settlement performance is governed by the size and area replacement ratio, not the diameter of columns. All curves produced by Priebe’s have the value of  $S/S_{uc} < 1$ . It should be noted that  $S$  in Priebe’s curve is the settlement for end bearing column for spread footing and not the floating columns as used in this study. The settlement ratios in this study are much higher than in Priebe’s curve. It can be seen that reduction of settlement ratio for all curves are steeper in this study than those in Priebe (1995) when the depth ratio increases.

### 3.3 Comparison with Published Field Data

The validity of Figs. 12 ~ 14 as design charts is assessed with a field data published by Kirsh (2009) where a load test was conducted on a group of 5 columns with 9.0 m in length installed within soft alluvium sediment of 20.0 m. The floating stone columns were loaded by a 3 m square footing. The area replacement ratio of the foundation system is 0.28. Undrained shear strength of the soft soil was determined to be 12 kPa to 18 kPa. The load test was conducted as a maintained load test with loading stages held over a period of 10 days in total. At the end of the first loading stage a total displacement of 9 cm was measured under a load 105 kPa. Since the settlement of a large group of end bearing columns was not measured at the same site,  $S_{uc}$  was predicted using Eq. (1). This results in  $S/S_{uc} = 1.3$  which is slightly lower than  $S/S_{uc} = 1.55$  determined from the design charts (extrapolation from figures of  $\alpha = 2$  and  $\alpha = 4$ ) which gives 10.7 cm settlement for floating stone columns. Slightly small settlement measured at site maybe due in part to the slow consolidation process of soft soil because of the short duration of

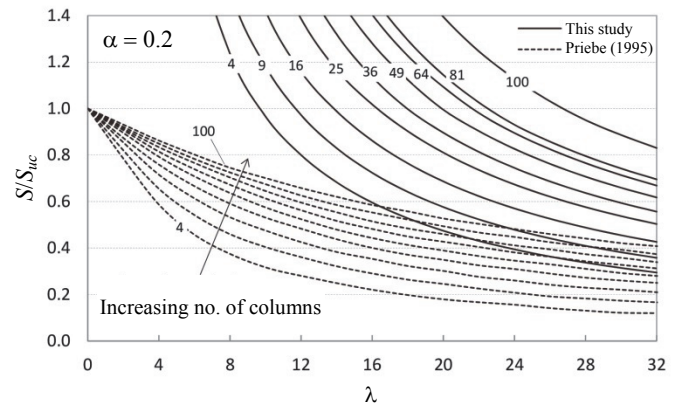


Fig. 15 Comparison of settlement ratio with Priebe (1995)

load test. Even though the above results provide reasonable agreement, however, more real case studies verifications are needed before the approach above can be used with confidence.

## 4. CONCLUSIONS

Finite element analyses were conducted to examine the influence of key parameters on the settlement ratio for both small and large column groups. Some conclusions can be made here:

### Large Column Groups

1. The settlement ratio of floating stone columns is much affected by the column length and the area replacement ratio.
2. A near-linear relationship exists between the settlement ratio and the column length.
3. Friction angle of column material has profound influence on the stress concentration ratio and moderate influence on the settlement ratio.
4. Load intensity and post installation lateral earth pressure have negligible influence on the settlement ratio and stress concentration ratio.
5. Predictive model was developed for large column groups to predict settlement ratio. It agrees well with Aboshi *et al.* (1979).

### Small Column Groups

1. The optimum length,  $L_{opt}$  is mostly controlled by the size of the footing ranging from 1.2D to 2.2D.
2. The optimum length is not much affected by the number of columns but more by the area replacement factors.
3. For a given number of stone columns, the settlement ratio increases when the area replacement ratio increases.
4. As the column groups become larger, the settlement ratio also increases.
5. The design charts generated in this study has been validated by a case study where reasonable agreement is obtained.

## REFERENCES

Aboshi, H., Ichimoto, E., Enoki, M., and Harada, K. (1979). “The compozer—A method to improve characteristics of soft clays by inclusion of large diameter sand columns.” *Proceedings of International Conference on Soil Reinforcement: Reinforced Earth and Other Techniques*, Ecole des Ponts ParisTech/Laboratoire Central des Ponts et Chaussées (ENPC/LCPC), Champs-sur-Marne, France, 1, 211–216.

- Aboshi, H. and Suematsu, N. (1985). "Sand compaction pile method: State-of-the-art paper." *Proceedings of the 3rd International Seminar on Soil Improvement Methods*, Singapore, 1–12.
- 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.
- Barksdale, R.D. and Bachus, R.C. (1983). *Design and Construction of Stone Columns, Volume I*, Washington, DC, USA: Federal Highway Administration.
- Castro, J. (2014). "Numerical modelling of stone columns beneath a rigid footing." *Computers and Geotechnics*, **60**, 77–87.
- Chai, J. and Pongsivasathit, S. (2010). "A method for predicting consolidation settlements of floating column improved clayey subsoil." *Frontiers of Architecture and Civil Engineering in China*, **4**(2), 241–251.
- Elkasabgy, M.A. (2005). *Performance of Stone Columns Reinforced Grounds*. M.Sc. Thesis. Zagazig University, Faculty of Engineering at Shobra, Cairo.
- Elshazly, H.A., Hafez, D.H., and Mossaad, M.E. (2008). "Reliability of conventional settlement evaluation for circular foundations on stone columns." *Geotechnical and Geological Engineering*, **26**(3), 323–334.
- Herle, I., Wehr J.J., and Arnold, M. (2008). Soil improvement with vibrated stone columns-influence of pressure level and relative density on friction angle. *Proceedings of the 2nd International Conference on the Geotechnics of Soft Soils*, Glasgow, 235–240.
- Hong, Y.K. (2003). *A Study on Characteristics of Bearing Capacity and Stress Concentration of Clay Ground Improved with Sand Compaction Piles*. Ph.D. dissertation, Kangwon National University, Korea.
- Ichmoto, E. (1981). Results of design and construction of sand compaction pile method. *The 36th JSCE Conference Discussion*, Japan, 51–55.
- Lawton, E.C. and Fox, N.S. (1994). "Settlement of structures supported on marginal or inadequate soils stiffened with short aggregate piers." *Vertical and Horizontal Deformations of Foundations and Embankments*, Geotechnical Special Publication, ASCE, 962–974.
- Lee, K.S. 2000. *Finite-Element Modeling of the Stone Column with Varying Cross Section*. M.Sc. Thesis. Myunggi University, Korea (in Korean).
- McCabe, B.A., Nimmons, G.J., and Egan, D. (2009). "A review of field performance of stone columns in soft soils." *Proceedings of the Institution of Civil Engineers-Geotechnical Engineering*, **162**(6), 323–334.
- Ng, K.S. and Tan, S.A. (2014). "Design and analyses of floating stone columns." *Soils and Foundations*, **54**(3), 478–487.
- Ng, K.S. and Tan, S.A. (2015). "Simplified homogenization method in stone column designs." *Soils and Foundations*, **55**(1), 154–165.
- Ng, K.S., Tan, S.A., and Sun, J. (2014). "A new approach to the estimation of settlement and ultimate bearing capacity of stone columns supported shallow foundation." *The 8th European Conference on Numerical Methods in Geotechnical Engineering*, Delft, 541–546.
- Priebe, H.J. (1995). "The design of vibro replacement." *Ground Engineering*, **28**, 31–37.
- Rao, B.G. and Ranjan, G. (1985). "Settlement analysis of skirted granular piles." *Journal of Geotechnical Engineering*, **111**, 1264–1283.
- Sehn, A.L. and Blackburn, J.T. (2008). "Predicting performance of aggregate piers." *The 23rd Central Pennsylvania Geotechnical Conference*, Hershey, Pennsylvania, 28–30.
- Tan, S.A. and Ng, K.S. (2013). "Stone columns foundation analysis with concentric ring approach." *Proceedings of the Third International Symposium on Computational Geomechanics*, Krakow, Poland, 495–504.
- Tan, S.A., Ng, K.S., and Sun, J. (2014). "Column groups analyses for stone column reinforced foundation." *From Soil Behavior Fundamentals to Innovations in Geotechnical Engineering*, GSP 233, ASCE, 597–608.
- Tan, S.A., Tjahyono, S., and Oo, K.K. (2008). "Simplified plane-strain modeling of stone-column reinforced ground." *Journal of Geotechnical and Geoenvironmental Engineering*, **134**(2), 185–194.
- Wood, D.M., Hu, W., and Nash, D.F.T. (2000). "Group effects in stone column foundations: Model tests." *Geotechnique*, **50**(6), 689–698.