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PARAMETRIC STUDY ON THE SETTLEMENT IMPROVEMENT FACTOR OF STONE COLUMN GROUPS

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ABSTRACT

In the design of floating stone column groups, the footprint replacement ratio is of great importance when attempting to reduce the amount of settlement. This paper shows the parametric study performed to determine the effects of other contributing parameters such as friction angle of column material, thickness of granular bed, column stiffness, soil stiffness and their relationships with footprint replacement ratio and loading intensity. The study was conducted using finite element method via the commercial geotechnical software PLAXIS. The parametric results have shown that the friction angle of the stone column material and the thickness of granular bed have the most profound effect on the settlement improvement factors. The influence of these factors are larger if the numbers of columns in a group is smaller, and the vice versa. Column stiffness is of less influence compared to soil stiffness and when the modulus ratio is larger than 20, the influence of these two parameters are very small and negligible. The stress transfer mechanism and the yielding characteristic were discussed pertaining to the influence of the key parameters on the settlement improvement factor. Finally, design recommendation was given to help the practicing engineer in designing the stone column group.

Keywords: floating stone column; settlement improvement factor; optimum length; finite element; parametric study.

1. INTRODUCTION

Lack of suitable land for development has prone the use of the marginal site. This site requires treatment before it can be used to facilitate construction of buildings and infrastructure. Stone column is therefore come into place as it allows more loads to be placed on the improved ground with lesser settlement induced. Stone column has gained its reputation through successful application in many case histories (Munfakh, Sarkar, & Castelli, 1983; Raju, 2002; Arulrajah, Abdullah, BO, & Bouazza, 2009; Stuedlein & Holtz, 2013). Most of the case histories are about improvement of soft ground for large structures such as embankments and industrial tanks, and not many are on small foundations supported structures. These small foundations are supported by limited number of columns and the design for this is different from the infinite columns grid. Current design approach to calculate the settlement of small

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stone column groups supported foundation are either simple in approach e.g. elasticity theory by Rao & Ranjan (1995) or semi-emperical in nature e.g. Lawton & Fox (1994).

In addition, the stone columns for small foundation can be of floating type as the stress concentration happens near the foundation base. However, none of the current design approach adopts optimum length concept except in the previous work of authors (Tan, Ng, & Sun, 2014). In the study, the optimum length, L_{opt} was suggested to be 2.2D where D is the diameter of footing. The optimum length was defined as length in which beyond it will not confers extra advantage. Besides, the relationship between the footprint replacement ratio, A_F and settlement improvement factor, n was established (Figure 1). Footprint replacement ratio, $A_F = A_c / A$, where A_c = area of columns, and A = footing area while settlement improvement factor, n = the ratio of settlement without stone column over settlement with stone column. The results demonstrated the importance of the footprint replacement ratio in reducing the settlement. The analyses was conducted using two dimensional finite element method where stone columns were simulated as series of concentric ring as shown in Figure 2 for 36 columns with A_F = 0.5. The details of the numerical model is describe in following section.

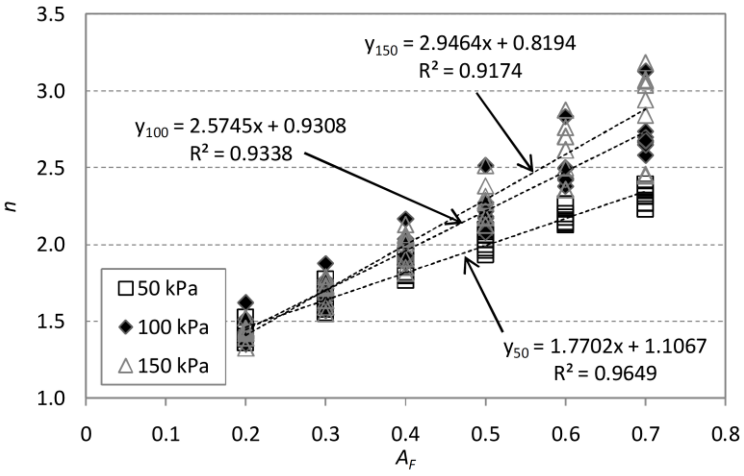

Figure 1: Settlement improvement factors.

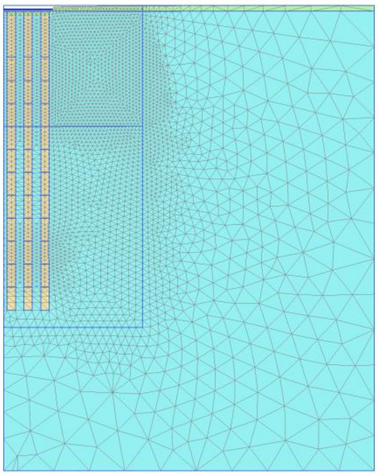

Figure 2: Numerical model.

This paper is the extension of work from Tan et al. (2014). Table 1 shows the material properties for the reference case used in parameteric study. The effects of other contributing parameters such as friction angle of column material (ϕ_c'), thickness of granular bed *(t)*, column stiffness (E_c), soil stiffness (E_s) and their relationship with footprint replacement ratio *(A_F)* and loading intensity *(q)* are presented in this paper. One parameter was altered from the reference case (Table 1) each time to investigate the influence or the sensitivity of each parameter on the settlement performance. Only the results of floating stone columns with optimum lengths are showed here.

Table 1: Materials properties for group columns.

Name		Soft soil	Stone column	Granular bed
Type		Drained	Drained	Drained
γ_b/γ_{sat}	[kN/m^3]	18	18	18
v'		0.3	0.3	0.3
E'	[kN/m^2]	3000	30000	10000
c'	[kN/m^2]	0.1	0.1	0.1
ϕ'	[°]	25	40	30
K_o		0.7	0.7	0.7

2. NUMERICAL MODEL

Finite element code PLAXIS 2D 2011 was adopted to analyze the spread footing supported by group of columns (i.e. 4, 9, 16, 25, 36, 49, 64, 81 and 100 columns). Axisymmetrical concentric ring model proposed by Elshazly, Hafez, & Mossaad (2008) was used to convert the off center columns to cylindrical equivalent rings. The properties in the ring element are kept the same as the stone column material while the radius and thickness of the rings are calculated so that the area ratio between column and the footings remains the same. The stone columns are always 1.0 m in diamter and this implys that change of footprint replacement ratio is obtained from changing the diameter of footing for a same group of columns. A uniform footing pressure of intensity *q* is applied over a footing of diameter *(D)* on a granular bed of 0.5 m thick. Stone columns with optimum length were used to perfomed the parametric study. The boundary and mesh sensitivity analyses were conducted for all the column configurations in order to reduce the influences of the mesh and boundary on the results of the simulations. The standard boundary conditions in the model were assumed such that the vertical boundaries are free vertically and constrained horizontally ($u_x = 0$; u_y = free) while the bottom horizontal boundary is fully fixed ($u_{x\&y} = 0$).

Uniform loading was applied through a footing with stiffness of $EI = 2.1 \times 10^5$ kN/m^2 which can be taken as relatively rigid material compared to soils below. The columns were simulated as "wish in place" which means the installation process was not modeled. In this study, the at rest earth pressure coefficient is assumed to be 0.7 for all the materials which value is higher than the one estimated by the Jaky's equation ($K_0 = 1 - \sin \phi'$) for normally consolidated soils but lower than hydrostatic value of 1 adopted by Priebe (1995). In numerical simulations, same initial stress was imposed for column and soil to reduce the problems of unbalanced forces during the loading stage. Ground water table is located just below the granular bed and drained analysis was conducted for all simulations.

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3. PARAMETRIC STUDY

3.1 Influence Of Column's Friction Angle

Figure 3 indicates the performance of the improved ground when the value of the column's friction angle increases ($\phi_c' = 40^{o}$ to 55^{o}) for the column groups of 9 and 64. Generally, the settlement reduces as the friction angle increases. As the load level increases, the influence of friction angle becomes more significant, as it is also evident from the length of plastic zone observed at the upper part as shown in Figure 4. More plastic points were developed and extended to a deeper depth for columns with lower friction angle (45°). While columns with higher friction angle (55°) exhibits very little plastic deformation since substantial overburden is required in order to fully mobilize the shear strength of the columns. This demonstrates the importance of maximum densification needed in course of the installation process.

The influence of friction angle of column material is larger in small column group than in big column group especially when the loading is large. In other words, the effect of slow development of irrecoverable plastic yielding in small group due to the higher friction angle is more profound than in large column group. Almost linear trend of improvement is observed as the footing replacement ratio increases. However the relationship of footprint replacement ratio, loading and friction angle of column material is not clear. For example, under 150 kPa loading, 9 columns group shows greater influence of column's friction angle as footprint replacement ratio increases, but on the contrary, the larger groups (i.e. 64 columns) demonstrate lesser influence of this friction angle as footprint replacement ratio increases. However, for small load level (i.e. $\leq$ 50 kPa), the influence of friction angle is negligibly small for high footprint replacement ratio in particular.

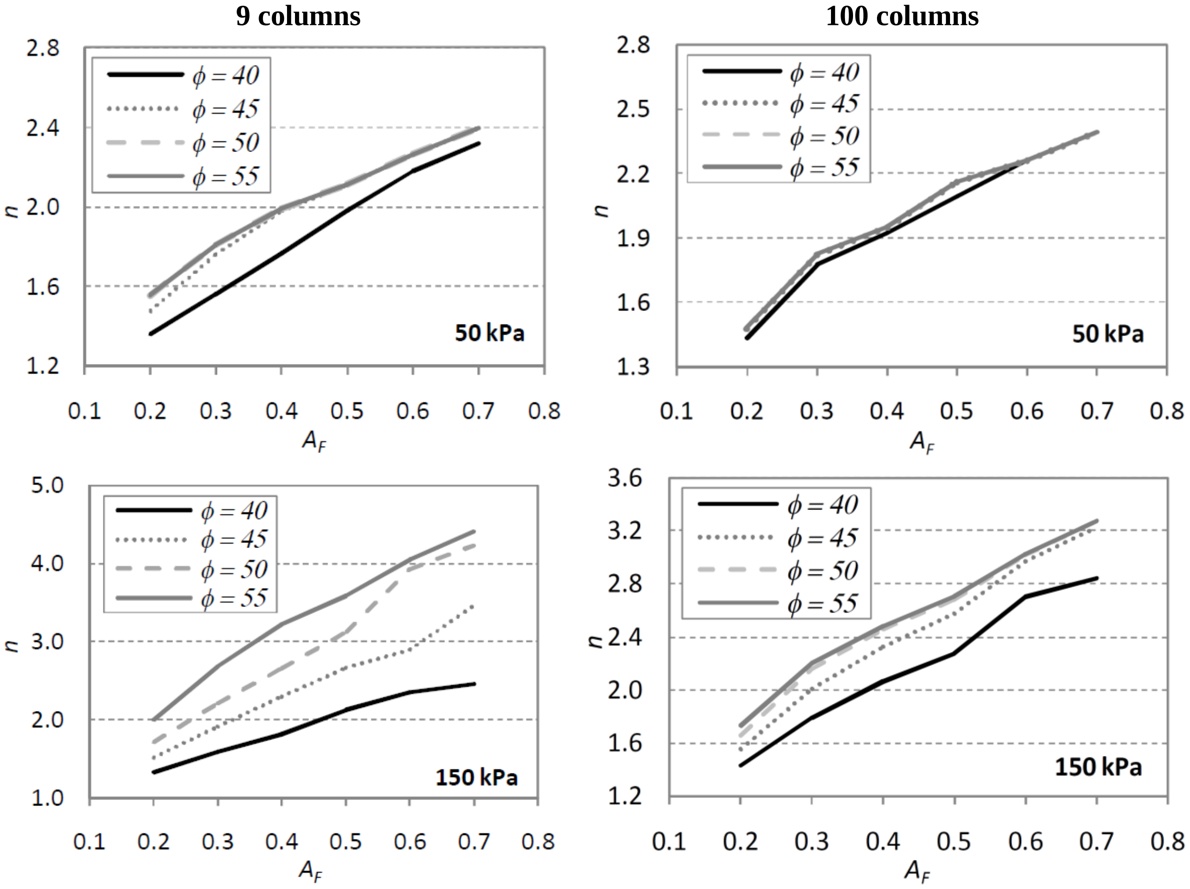

Figure 3: Influences of stone column's friction angle.

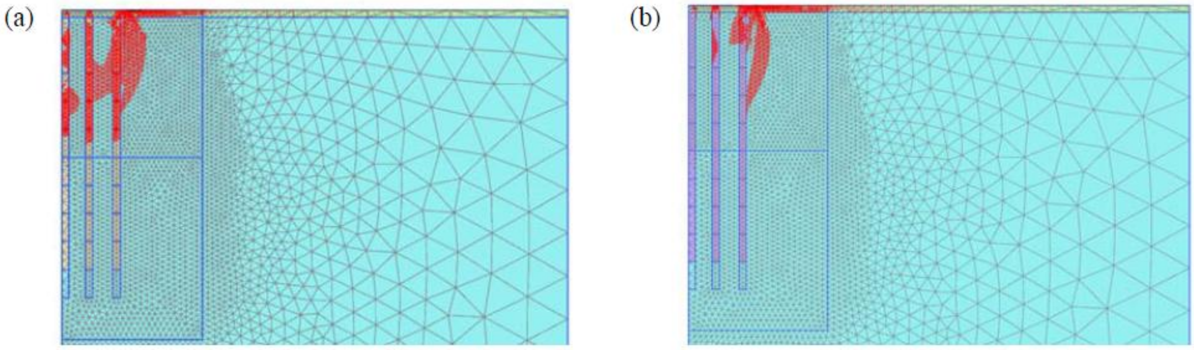

Figure 4: Plastic points for A_F = 0.3, 25 columns group with (a) c' = 45^{o} and (b) c' = 55^{o}.

3.2 Influence Of Granular Bed Thickness

The thickness of the granular bed was half meter thick in the reference case. The thickness was then varied to 1.0 m and 1.5 m to examine the influence of the thickness to the improvement factors. For better comparison, the thickness of the non-improved ground is varied accordingly as well. Figure 5 shows the influence of this variable to the settlement improvement factors. Increase of granular bed thickness reduce the settlement because of the higher stiffness and higher friction angle of the granular bed material compared to the soft soil below, true for both of the treated soil and the untreated soil. However, if the ratio of settlement is compared, it was found that the settlement improvement ratio reduces as the thickness increases. In other words, the contribution of the stone columns to the performance of the footing system is lessened.

The influence of the granular bed thickness is greater as the footprint replacement ratio increases. Since the number of column in a group is unchanged, larger replacement ratio would also means smaller diameter of footing. As the size of the footing is smaller, then the effect of the thickness is relatively larger. This effect is the same as the number of group becomes larger. Hence it is the size of the footing that governs the influence of the granular bed thickness. Separate study was done to examine the influence of shear strength of granular bed. Negligible influence was observed for different friction angle (35^o, 40^o, 45^o) of granular bed for loading range of 50 kPa to 150 kPa. The details of the results are not discussed here.

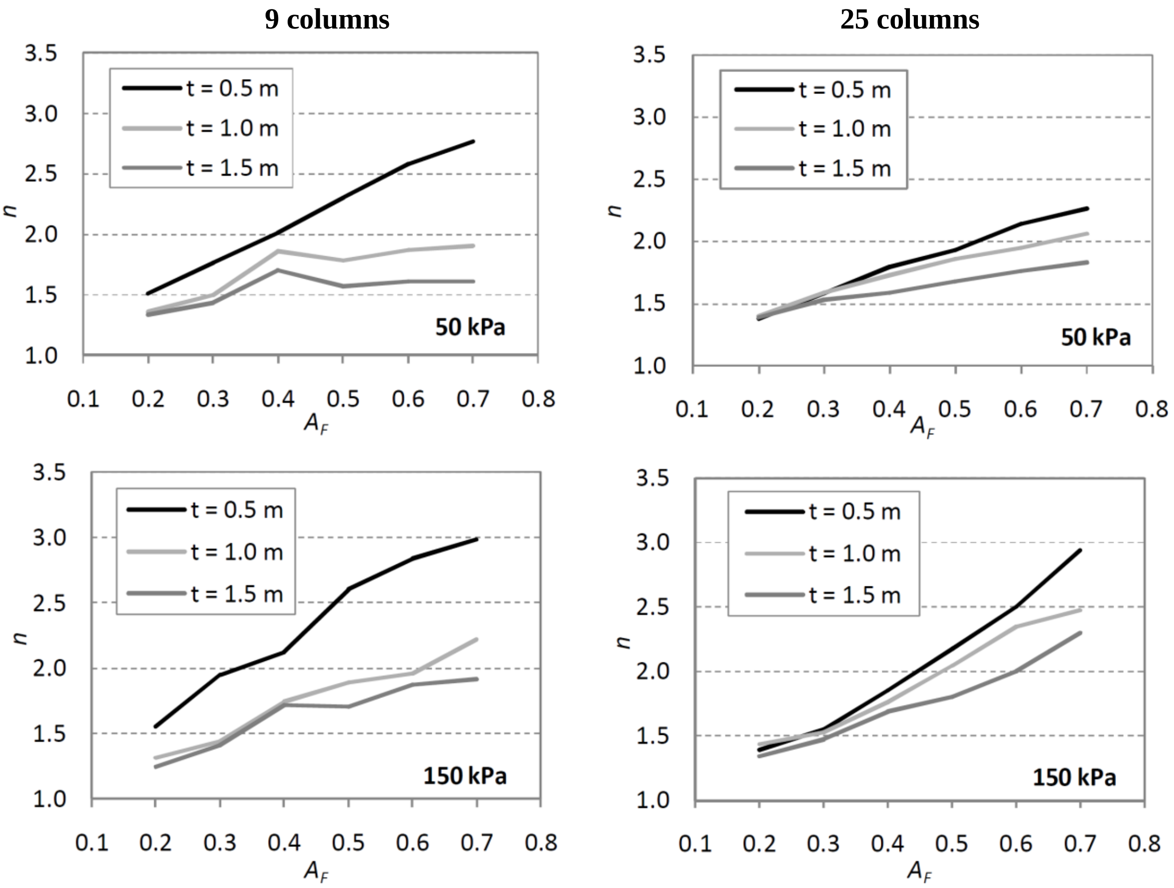

Figure 5: Influences of granular bed thickness.

3.3 Influence Of Column Stiffness

Stone columns are much stiffer than the surrounding ground. However, the stiffness of column is much dependent on the lateral support given by the soil around the column since the column material is a cohesionless material. In this study, columns stiffness are varied from E_c = 30000 kN/m^2 (reference value) to 15000 kN/m^2, 60000 kN/m^2, 90000 kN/m^2, 120000 kN/m^2, and 150000 kN/m^2 (i.e. from modular ratio, E_c/E_s of 10 to 5, 20, 30, 40, 50) while the soil stiffness, E_s remain the same as 3000 kN/m^2. Figure 6 shows the load-settlement curves for 9 and 49 columns respectively. The influence of column stiffness is very minor especially when the modular ratio is greater than 20 (E_c = 30000 kN/m^2). The influence is even negligible when the column groups are small as shown in the results of 9 columns group. Low modular ratio i.e E_c/E_s = 5 has adverse impact on the settlement performance and the effect is more pronouced in larger column group. However, in practice, such a low modular ratio is rarely encountered unless the column is not well compacted due to poor workmanship or that the original ground is extremely soft, for example, peaty clay with undrained shear strength less than 5 kN/m^2. In addition the impact of different column stiffness on settlement performance is greater when the footprint replacement ratio increases and this is more obvious in larger group of columns.

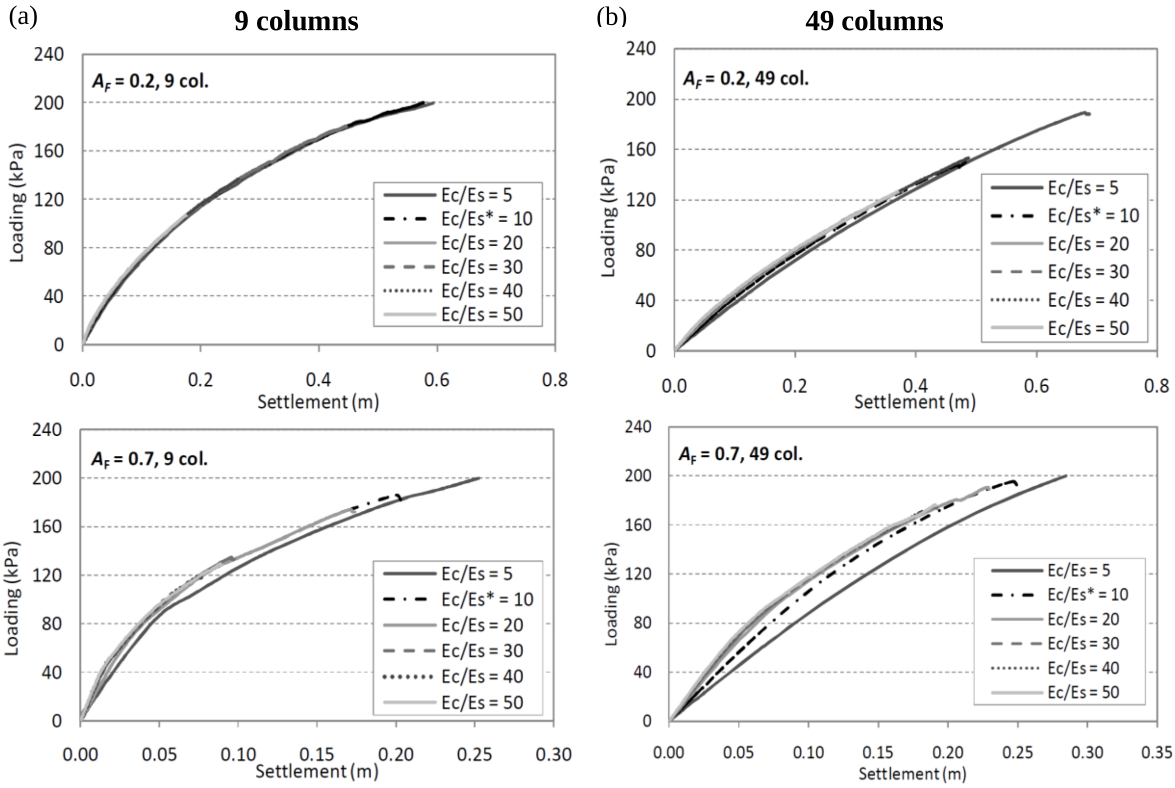

Figure 6: Influences of stone column’s friction angle.

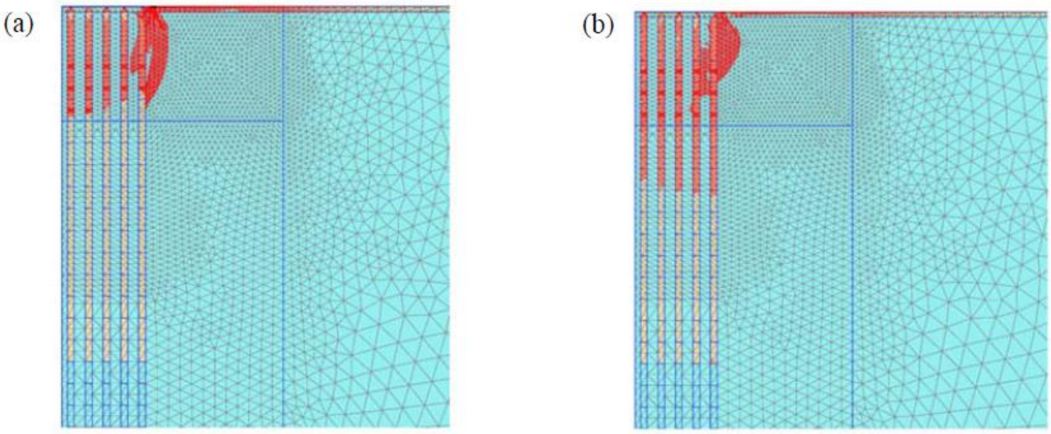

Figure 7: Yielding zone (a) E_c = 15000kN/m^2; and (b) E_c = 150000 kN/m^2.

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Figure 7 shows the yielded zone is larger for footing improved with higher stiffness as in the example of 100 columns group with A_F = 0.4. On the other hand, columns with higher stiffness tends to produce friction support to a greater depth compare to the columns with lower stiffness although the total settlements are smaller in the case of columns with higher stiffness. As a result, the deformation mechanishm is pushed downward and this has created larger toe movements in columns with higher stiffness viz. Figure 8. This effect can be easily observed if the loading is much larger than the cases here.

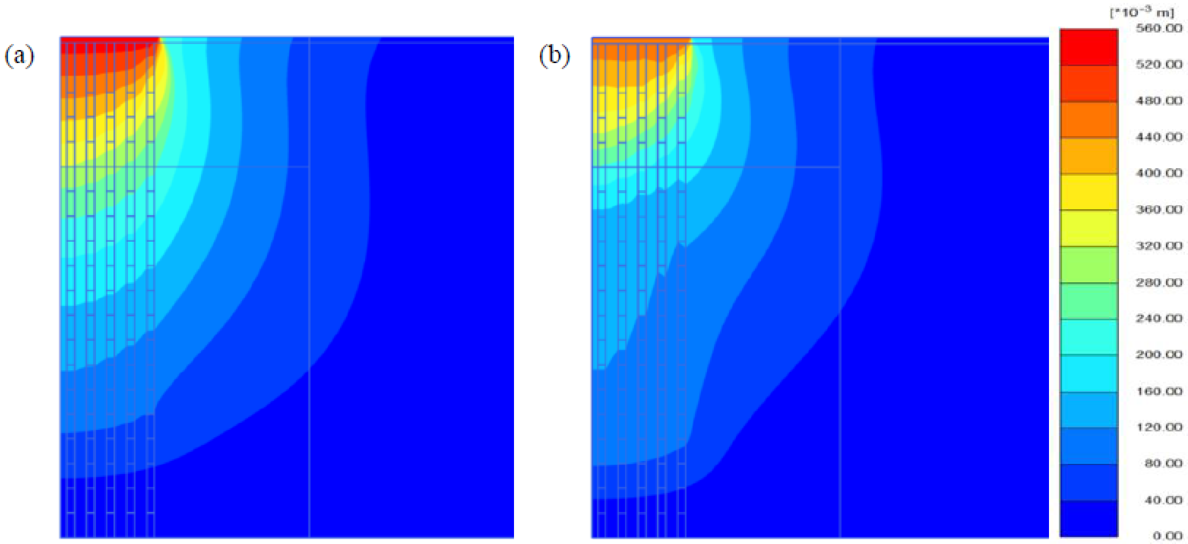

Figure 8: Total displacement shading (a) E_c = 15000 kN/m^2; and (b) E_c = 150000 kN/m^2.

3.4 Influence Of Soil Stiffness

Similar approach as above was adopted, the soil stiffness are varied from E_s = 3000 kN/m^2 to 6000 kN/m^2, 1500 kN/m^2, 1000 kN/m^2, 700 kN/m^2, and 600 kN/m^2 (i.e. modular ratio E_c/E_s from 10 to E_c/E_s = 5, 20, 30, 40, 50) while the column stiffness, E_c remain the same as 30000 kN/m^2. Figure 9 presents the plots of settlement improvement factor against different modular ratios for 9 and 49 columns respectively. Compared with the influence of column stiffness, the influence of soil stiffness on the settlement performance is more significant especially when the loading is small e.g. 50 kPa. This is probably due to the improved ground that still behave mainly as eleastic under small loading range. While the modular ratio is small i.e. E_c/E_s = 5, the settlement improvement factors for loading case of 50 kPa is lower than that for 100 kPa, but when the E_c/E_s larger than about 15, the settlement improvement factors for 50 kPa is higher than that for 100 kPa. This is because when the surrounding soil is weak, the improved ground shear strength and equivalent stiffiness are also low and hence the ground exhibit mostly plastic behaviour under higher loading. Another explanation to this is that in untreated ground, the soil with high stiffness exhibits stronger resistance to the applied load (high tangent gradient in load-settlement curve) and this is more influential than the ground improvement obtained with stone columns where the contribution of stone column comes in at a later stage of loading.

Under the same loading, group with larger column number gives larger influence in the settlement improvement factor as the modulus ratio increases. The reason lies on the greater interactions among columns in larger groups than in smaller groups. The same explanation is also applied to high footprint replacement ratios where the columns spacing are closer and the footings are smaller.

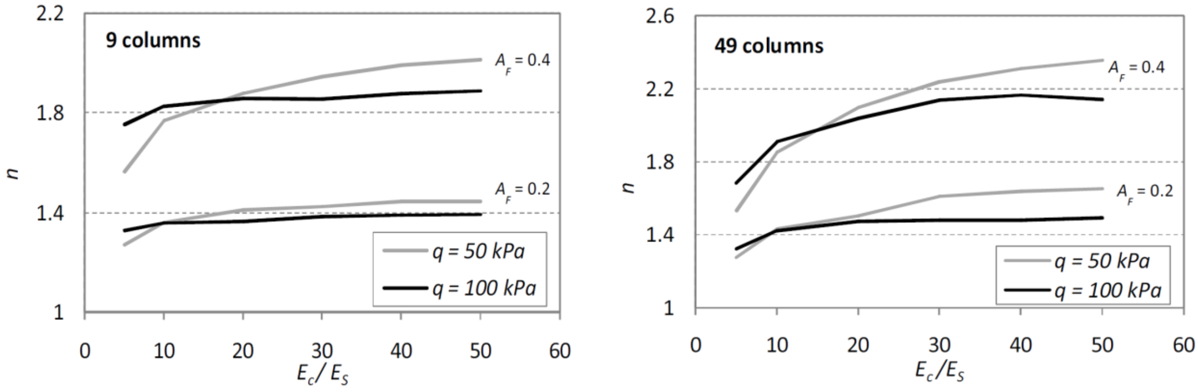

Figure 9: Influence of soil stiffness on settlement improvement factors for column groups of 9 and 49.

Columns surrounded by low stiffness soil attracted more loads than columns surrounded by higher stiffness soil as depicted in Figure 10. Stress concentration ratios, n_s (ratio of stress in the stone columns to that in the intervening ground) for soil with E_s = 600 kN/m^2 are 3.04 and 3.00 for the inner and outer ring of columns respectively, while for case of E_s = 6000 kN/m^2 the stresss concentration ratios for the inner and outer ring of columns are n_s = 2.0 and n_s = 2.6 respectively. In other words, there are more stress relief in the soil with lower stiffness compared to the soil with higher stiffness.

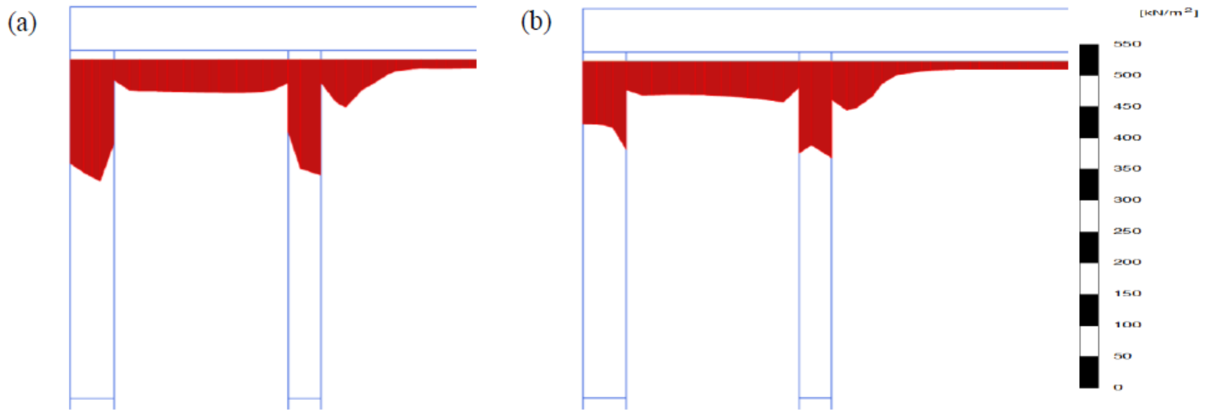

Figure 10: Stress concentration for 9 columns group at 50 kPa for soil with (a) E_s = 600 kN/m^2, and (b) E_s = 6000 kN/m^2.

Lower stiffness of soil results in larger deformation hence the development of plastic points at the upper portion of footing are extended further compared to the results for soil with higher stiffness. This can be clearly seen in smaller loading case i.e. 50 kPa as shown in Figure 11a & Figure 12a where significant yielding has occurred for soil with stiffness of 600 kN/m^2 in contrast to soil stiffness of 6000 kN/m^2 where little yielding of improved ground occurred around the outer columns. There exists an intrinsic mechanism when the stone column contribution kicked in at early stage (during small loading applied) when the surrounding soil is soft. Figure 11 (a) shows substatial development of plastic points along the columns while the surrouding soil is still mainly in the elastic state. As the load increases, the surrounding soil around the columns are turned into plastic state (Figure 11b &12b).

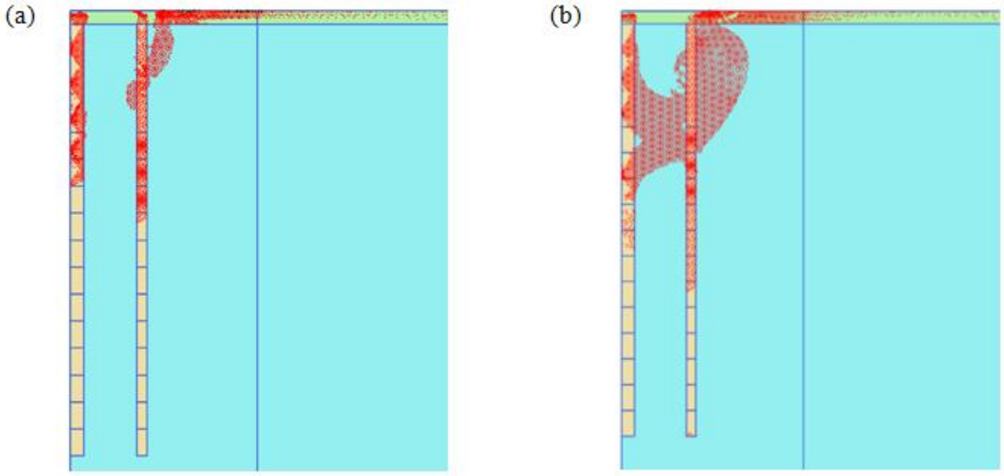

Figure 11: Plastic points for 49 columns group with E_s = 600 kN/m^2 group under loading of (a) 50 kPa; and (b) 100 kPa.

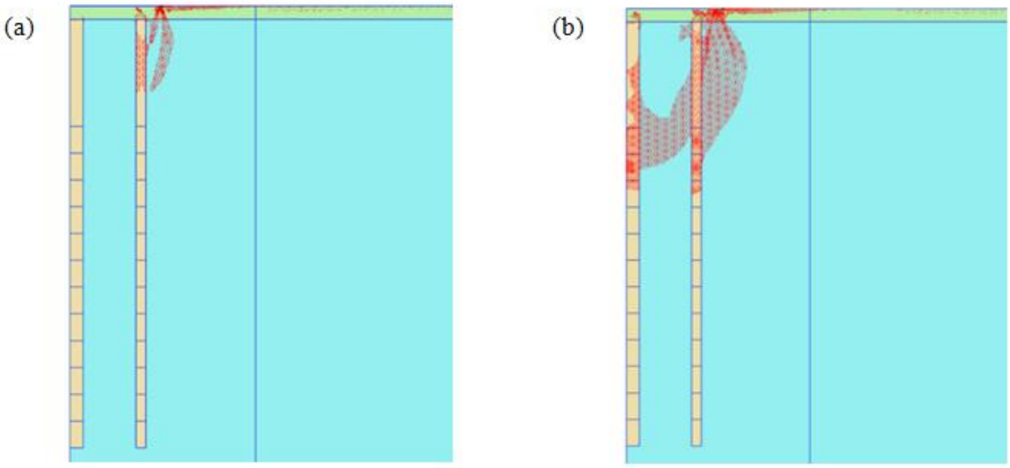

Figure 12: Plastic points for 49 columns group with E_s = 6000 kN/m^2 group under loading of (a) 50 kPa; and (b) 100 kPa.

4. CONCLUSION

A parametric study with numerical approach was carried out to investigate the influence of other key parameters on the settlement improvement factors of stone column improved foundation. The conlusion drawn pertaining to the drained analysis are as follows:

a) Friction angle of column material has moderate influence on the settlement improvement factors especially when the loading is large and the number of columns is small.

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b) Increasing the thickness of granular bed results in reduction of settlement performance particularly for small footing size.

c) When the soil stiffness is unchanged while the columns stiffness increases, the settlement reduction is negligible except when the modulus ratio is small i.e. $E_c/E_s = 5$.

d) The influence of soil stiffness is more than the influence of column stiffness. Better settlement improvements are achieved when the soil is softer and/or subjected to a smaller loading.

REFERENCES

Arulrajah, A., Abdullah, A., BO, M. W., & Bouazza, A. (2009). Ground improvement techniques for railway embankments. *Ground Improvement (Proceedings of the ICE), 162*(GI1).

Elshazly, H. A., Hafez, D. H., & Mossaad, M. E. (2008). Reliability of conventional settlement evaluation for circular foundations on stone columns. *Geotechnical and Geological Engineering, 26*(3), 323–334.

Lawton, E. C. & Fox, N. S. (1994). Settlement of structures supported on marginal or inadequate soils stiffened with short aggregate piers. In *Vertical and Horizontal Deformations of Foundations and Embankments* (pp. 962-974). ASCE.

Munfakh, G. A., Sarkar, S. K., & Castelli, R. J. (1983). Performance of a test embankment founded on stone columns. *Proceedings of the International Conference on Advances in Piling and Ground Treatment for Foundations, London*, 193-199.

Priebe, H. J. (1995). The design of vibro replacement. *Ground engineering*, *28*, 31–37.

Raju, V. R. (2002, March). Vibro replacement for high earth embankments and bridge abutment slopes in Putrajaya, Malaysia. *In International Conference on Ground Improvement Techniques, Malaysia*, 607-614.

Rao, B. G. & Ranjan, G. (1985). Settlement analysis of skirted granular piles. *Journal of Geotechnical Engineering, 111*, 1264-1283.

Stuedlein, A. W. & Holtz, R. D. (2011). Analysis of footing load tests on aggregate pier reinforced clay. *Journal of Geotechnical and Geoenvironmental Engineering, 138*(9), 1091-1103.

Tan, S. A., Ng, K. S. & Sun, J. (2014). Column Groups Analyses for Stone Column Reinforced Foundation. *Geotechnical Special Publication: From Soil Behavior Fundamentals to Innovations in Geotechnical Engineering. ASCE, Reston. GSP 233,* 597-608.

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