Settlement analysis of column-like elements

Analyse du tassement des éléments en forme de colonnes

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ABSTRACT: In recent years, column-like elements have been recognized as an effective ground improvement method to support superstructures constructed on soft soils. Different types of columns are characterized by different construction techniques, rigidity and materials used to construct these columns. This paper uses a new analytical method derived to assess the performance of column-like elements under applied external loads. The critical length of column-like element is determined to estimate the column length required to resist applied load solely by the floating column. The analytical method is used together with the Finite Element Analysis to investigate the effectiveness of stone columns in reducing the settlement of pad and strip footings using the relative settlement reduction (RSR). Overall, the simplified analytical model yields reasonable results when predicting the settlement improvement of small group footings due to the installation of stone columns.

RÉSUMÉ : Ces dernières années, des éléments en forme de colonnes ont été reconnus comme une méthode efficace d'amélioration du sol pour soutenir les superstructures construites sur des sols mous. Différents types de colonnes sont caractérisés par différentes techniques de construction, rigidité et matériaux utilisés pour construire ces colonnes. Cet article utilise une nouvelle méthode d'analyse dérivée pour évaluer la performance des éléments en forme de colonnes sous des charges externes appliquées. La longueur critique de l'élément de type colonne est déterminée pour estimer la longueur de colonne requise pour résister à la charge appliquée uniquement par la colonne flottante. La méthode analytique est utilisée avec l'analyse par éléments finis pour étudier l'efficacité des colonnes de pierre dans la réduction du tassement des semelles isolées et filantes en utilisant la Réduction Relative de Tassement. Dans l'ensemble, le modèle analytique simplifié donne des résultats raisonnables lorsqu'il s'applique à la prévision de l'amélioration du tassement des semelles de petits groupes grâce à l'installation de colonnes en pierre.

KEYWORDS: ground improvement, stone columns, settlement, soft clay.

1 INTRODUCTION

Settlement performance of stone columns is often analysed by numerical methods. Several analytical and empirical design methods are incorporated in numerical analysis software for assessing the settlement reduction due to the installation of stone columns (Al Ammari & Clarke 2016). The design of stone columns in soft clays is usually governed by performance (settlement) rather than the column bearing capacity to support applied load (Killeen 2012). Most design methods in the UK use Priebe's method to assess settlement improvement (Priebe 1995).

Al-Ani & Wanatowski (2017) performed a numerical study of an axisymmetric model (an efficient mathematical means of modelling stone column grids) using a Hardening Soil model and compared it with an analytical model developed by Satibi (2009). The analytical approach proposed by Satibi (2009) was then modified to evaluate the performance of an infinite grid of floating stone columns using the relative settlement reduction (RSR) ratio. It was found that the RSR ratio increased with the increasing column length. Furthermore, the RSR ratio was about 45-60% at the critical column length defined as the minimum required length to resist the applied load solely by a floating stone column (Al-Ani & Wanatowski 2017).

In the current paper, the approach presented by Al-Ani & Wanatowski (2017) is applied in conjunction with the design charts developed by Priebe (1995) to predict the settlement of a single pad and strip footings. The aim of the paper is to provide practicing engineers with a simple tool for assessing the foundation settlement in soft soils reinforced with stone columns.

2 METHODOLOGY

The analytical approach applied in this study is based on the unit cell concept where a uniformly distributed surcharge is applied on the top of the stone column, as shown in Figure 1.

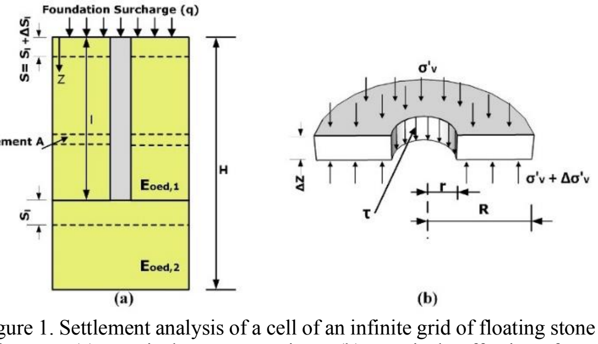


Figure 1. Settlement analysis of a cell of an infinite grid of floating stone columns: (a) vertical cross section, (b) vertical effective force equilibrium of element A (after Satibi 2009).

This method was used to determine the critical length of stone column and to assess the effectiveness of stone columns, with the unit cell radius, R = 0.50 to 0.75m and a stone column radius r = 0.3m. The analytical model derivations are presented in Al-Ani & Wanatowski (2017) and will not be repeated in this paper.

The two modifications of the analytical model proposed by Satibi (2009) included (1) using a lateral reduction factor (RF) in lieu of $K_s \tan\delta$ to simulate the behaviour of short columns (length/width ratio of less than 10 to 12), and (2) applying additional settlement reduction factor to calculate the settlement of spread footings.

A hypothetical soft soil profile was considered in the build-up of the analytical model to perform a comparison between the analytical model and the Finite Element Analysis (FEA). The soil and stone material properties (Table 1) used in the FEA are representative of the most of soft soils where the use of the stone columns as an improvement technique is of growing interest.

Table 1. Material parameters used in Finite Element Analysis

Parameter and unit	Soft soil	Stone column
φ' (°)	25	45
c' (kPa)	0.1	0.1
ψ (°)	0	15
γ (kN/m³)	16.5	19
$E_{50}^{ref} = E_{oed}^{ref}$ (MPa)	1.5	70
E_{ur}^{ref} (MPa)	4.5	210
υ_{ur} (-)	0.2	0.2
m (-)	1	0.5

Finite Element program PLAXIS 2D was used to model the stone column behaviour. The soft soil and the stone were both modelled using the Hardening Soil model. The stone column reinforced foundation was analysed as the axisymmetric soil model similar to that used in the analytical approach. The geometry and mesh used in FEA are shown in Figure 2. The external boundary has a radius of 0.5 m to 0.75 m to simulate typical column spacing of 1.0 m to 1.5 m and the stone column radius is equal to 0.3m. In the subsequent FE and analytical analyses, the settlement behaviour of various configurations of soft soil thickness and stone column spacing were examined for an applied pressure up to 50 kPa (a typical working stress for a stone columns installed in the soft clay). Boundary conditions were applied by preventing the horizontal displacement at the vertical side of the mesh and preventing both the vertical and horizontal movements at the bottom. The ground water level was assumed to be at the ground level.

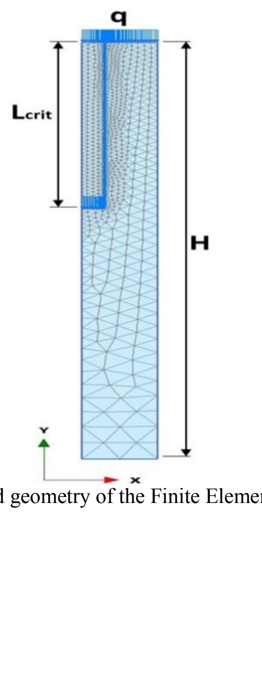


Figure 2. Mesh and geometry of the Finite Element model.

Selected configurations of footings analysed in this paper are illustrated in Figure 3. The RSR was predicted for a single column, 2x2, 3x3 groups and a row of 2 columns under a pad footing. The footings are 0.6 m thick and the depth of the footing is 0.6 m below ground surface. A square grid of columns spaced at 1.0, 1.2, and 1.5 m was used in the analyses. The footing overhang was located at the half the column spacing (0.5s) from the centreline of the outer row. The settlement performance of different stone column arrangements was calculated for the applied pressure of 50kPa using soil properties summarised above in Table 1. Design charts developed by Priebe (1995) were used to predict the settlement of all the footing configurations shown in Figure 3 (Al-Ani 2020).

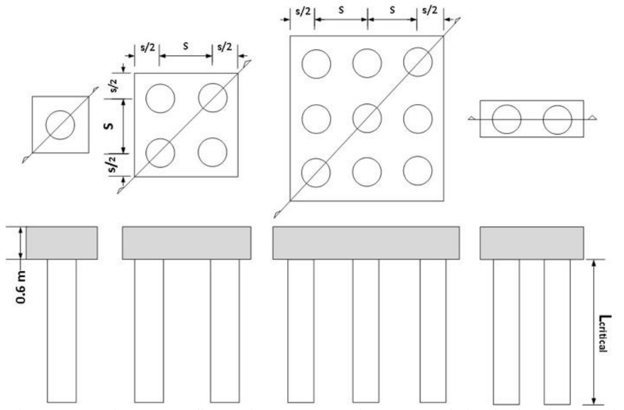


Figure 3. Column configurations to examine RSR of single footings (Al-Ani 2020).

3 RESULTS

3.1 *The critical length of stone column*

Firstly, the analytical model was used to predict the critical length of the stone column and to assess its effectiveness (Table 2).

Table 2. The critical column length ($L_{critical}$) and L/d ratio predicted by the analytical model

	$L_{critical}$			L/d		
	Column spacing s(m)			Column spacing s(m)		
RF	1.0	1.2	1.5	1.0	1.2	1.5
0.42	3.13	4.06	5.37	5.22	6.77	8.95
0.5	2.86	3.72	4.92	4.76	6.2	8.2

It is interesting to note from Table 2 that the critical column length suggested by the analytical model is consistent with the findings of Hughes & Withers (1974), Narasimha Rao et al. (1992), McKelvey et al. (2004), and Black (2006). Hughes & Withers (1974) also suggested that the column shorter than 4d would fail by punching where it was found that the shear stress and the end bearing pressure are lower than the bulging capacity for columns shorter than L<4d.

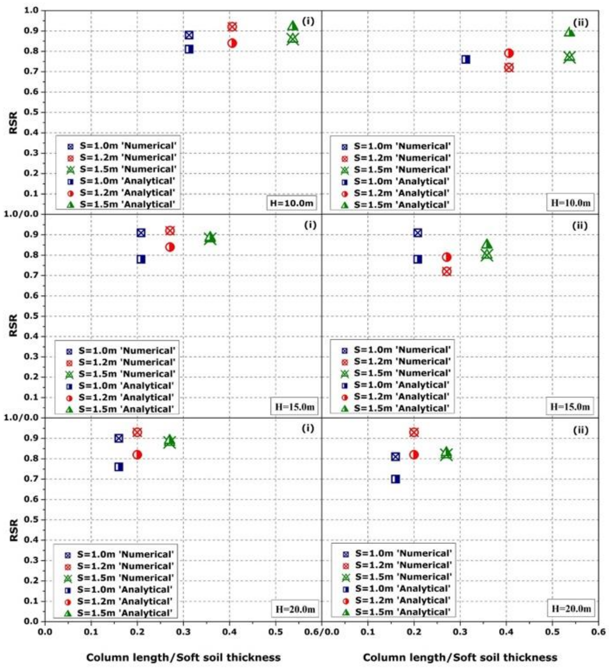
A critical column length appears to exist between 5d to 7d beyond which no further increase in the ultimate capacity is gained (Narasimha Rao et al., 1992). McKelvey et al. (2004) suggested that there is some merit in installing columns longer than the bearing capacity critical column length to control settlement. The findings of Black (2006) are consistent with McKelvey et al. (2004) who carried out a laboratory study on small groups of columns and suggested that the ratio between the critical column length to the column diameter exists and lies in the range L/d= 6-10. Based on these studies, it is suggested that the column critical length lies in the range L/d= 4 to 10. The column critical length predicted by the analytical model suggests that it lies in the range L/d= 4.76 to 8.95, as shown in Table 2.

The reduction factor (RF) was assumed to be equal to 0.42 where the coefficient of lateral earth pressure K_s was equal to 1.0 to account for the installation effect of the stone columns, which is consistent with the value proposed by Priebe (1995). However, a value of the lateral earth pressure of K_s=1.2 (corresponding to RF = 0.5) was used to investigate the impact of the column installation effect on reducing the footing settlement. The RF of 0.42 and 0.5 were derived assuming that the soft soil is a non-dilating soil. Therefore $\tan\delta = \sin\phi'$ for the ultimate skin friction as indicated by Vermeer and Sutjiadi (1985) and Satibi (2009).

3.2 *Settlement improvement of single and strip footings*

In general, the bearing capacity of stone columns is a less stringent design criterion than the settlement in soft soils (Al-Ani 2020). Considerable advances have been made in the soft soils constitutive models to incorporate the effect of bonding, creep and anisotropy in FEA. However, there is a very limited use of such models by geotechnical engineers in ground improvement design due to their complexity and the requirements of detailed and expensive soil investigations which are not always available. The most common design methods in stone column practice involve some empiricism in formulae derivations and many simplifying assumptions. This was also the case in developing the design charts by Priebe (1995) used in the current study.

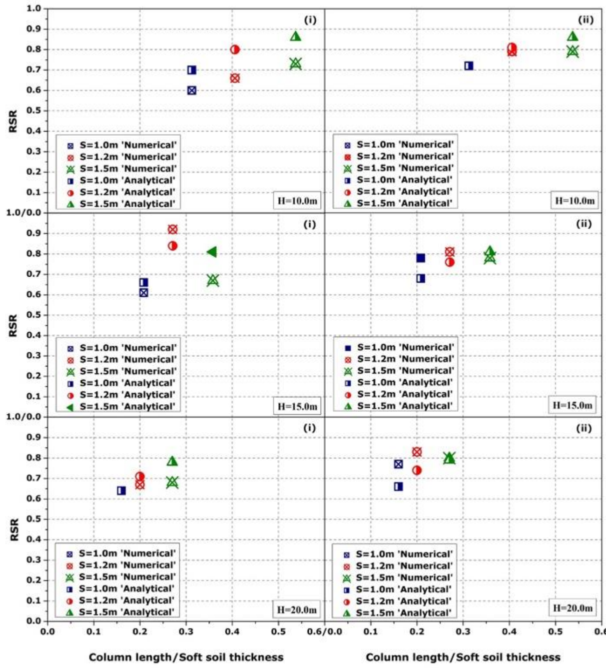
The influence of column arrangement on the RSR is shown in Figures 4 and 5. It can be seen that in some arrangements the maximum difference between RSR predicted by FEA and analytical model is about 14%. However, most of the results predicted less than 10% difference in the calculated RSR values using FEA and the analytical model. Therefore, it can be concluded that the proposed analytical tool could be used to estimate the effectiveness of the stone columns installed under single footings at preliminary design stage. However, the settlement of the footing should be verified by measurements made after the construction of sacrificial or working stone columns.



(a) (b)

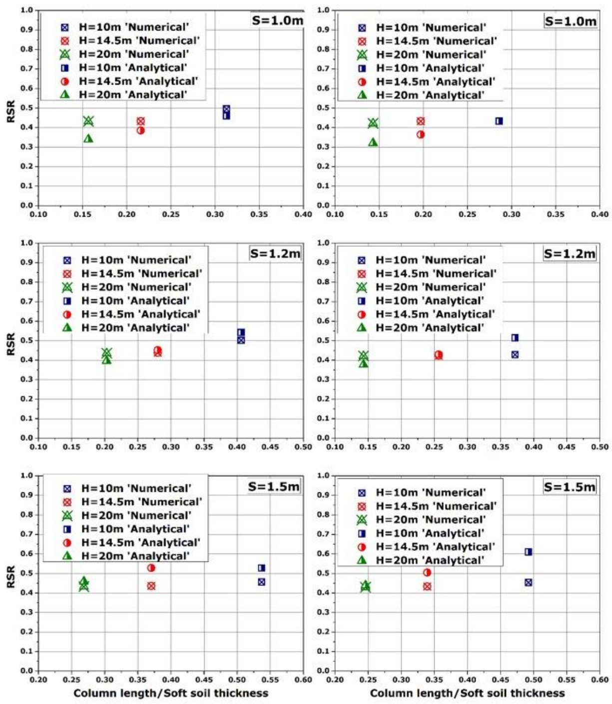
Figure 4. Variation of RSR with the critical column length to the soil thickness ($L_{critical}$/H) for (a) single footing, and (b) 2x2 group.

For comparison, the variation of RSR with the ratio of column critical length to the soft soil thickness ($L_{critical}$/H) for an infinitely wide surcharge of 50 kPa is shown in Figure 6. In general, the effectiveness of reinforcing soft soils with stone columns corresponds to the column critical length in the range of 0.35 to 0.6 times soft soil thickness (H). However, in design practice, the effectiveness predicted in this simplified method need to be assessed alongside the total and differential settlements to evaluate if the ground improvement satisfies specific project performance criteria.



(a) (b)

Figure 5. Variation of RSR with the critical column length to the soil thickness ($L_{critical}$/H) for (a) 3x3 group, and (b) 2-column footing.



(a) (b)

Figure 6. Variation of RSR with critical column length to the soil thickness ($L_{critical}$/H) for (a) RF= 0.42 and (b) RF= 0.5 at the applied pressure of 50 kPa.

Figure 6 shows that a good agreement exists between both the FE analysis and the analytical model in predicting the RSR when the soft layer thickness over the critical column length ratio ($H/L_{critical}$) = 2 to 5.

The comparison of Figures 4, 5 and 6 also reveals that the stone columns constructed to support pad and strip footings are more effective than the stone columns beneath a wide loaded area in reducing the foundation settlement with a column critical length in the range of 0.6 to 0.94 times the soft soil thickness (H), as indicated in Figures 4 and 5. Therefore, the installation of the stone columns to support pad footings is more effective in reducing settlement compared to an infinite grid of columns supporting an infinitely wide load (Figure 6).

4 CONCLUSIONS

In this paper, the analytical model developed by Satibi (2009) is modified to predict the foundation relative settlement reduction ratio (RSR). The results obtained from the analytical model are compared with those obtained from the FEA to evaluate the influence of installing a stone column upon the settlement performance of a footing. The effectiveness of the stone columns was quantified using the RSR, which was identified as the ratio of the reduced footing settlement due to the column installation to that of the total footing settlement without any reinforcement. The analytical model was further modified by introducing Priebe (1995) reduction factors to enable the calculation of RSR for the spread and pad footings.

The main conclusions are summarized below:

- The effectiveness of the stone columns measured by the RSR ratio lies in the range of 35% to 60%.
- The RSR ratio predicted by the FEA agrees well with that obtained from the analytical model when the soft layer thickness over critical column length ratio ($H/L_{critical}$) = 2 to 5.
- It appears that the simplified analytical model yields reasonable results when predicting the settlement improvement of small group footings due to the installation of stone columns. The maximum difference between RSR predicted by FEA and analytical model is about 14%; however, most of the results predicted less than 10% difference between the two models.
- The RSR ratio of a stone column constructed to support pad and strip footings is in the range of 0.6 to 0.94. This implies that the stone columns constructed to support pad and spread footings were more effective in reducing settlement compared to an infinite grid of columns supporting an infinitely wide load.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

Al Ammari K. and Clarke B.G. 2016. Predicting the effect of vibro stone column installation on performance of reinforced foundations. *International Journal of Civil and Environmental Engineering* 10 (2), 111-117.

Al-Ani W. 2020. Numerical analysis of ground improvement using column-like elements. *PhD thesis*, University of Nottingham, United Kingdom.

Al-Ani W. and Wanatowski D. 2017. Settlement analysis of floating stone columns, *Proc. 19th Int. Conf. Soil Mech. and Geotech. Eng.,* Seoul, South Korea, 2469-2472.

Black J.A. 2006. The settlement performance of a footing supported on soft clay reinforced with vibrated stone columns. *PhD thesis*, Queen's University of Belfast.

Hughes J.M.O. and Withers N.J. 1974. Reinforcing of soft cohesive soils with stone columns. *Ground Engineering* 7 (3), 42-49.

Killeen M. 2012. Numerical modelling of small groups of stone columns. *PhD thesis*, College of Engineering and Informatics, National University of Ireland, Galway.

McKelvey D., Sivakumar V., Bell A. and Graham J. 2004. Modelling vibrated stone columns in soft clay. *Proc. of the ICE Geotechnical Eng.* 157 (3), 137-329.

Narashimha Rao S., Madhiyan M. and Prasad Y.V.S.N. 1992 Influence of bearing area on the behaviour of stone column. *Proc. Indian Geotech. Conf.,* Calcutta, India, 235-237.

Priebe H.J. 1995. The design of vibro replacement. *Ground Engineering* 28 (10), 31-37.

Satibi S. 2009. Numerical analysis and design criteria of embankments on floating piles. *PhD thesis*, University of Stuttgart, Germany.

Vermeer P.A. and Sutjiadi W. 1985. The uplift resistance of shallow embedded anchors. *Proc. 11th Int. Conf. Soil Mech. Geotech. Eng.,* San Francisco, 1635-1638.